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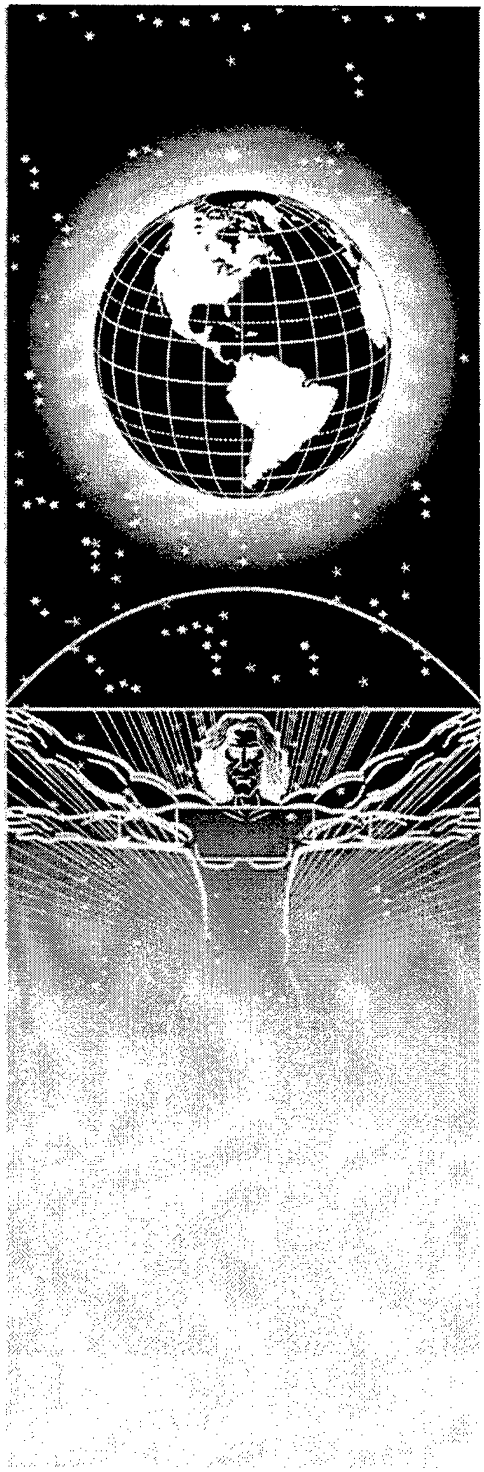

UNITED STATES AIR FORCE RESEARCH LABORATORY

ECOLOGICAL INTERFACE DESIGN FOR COMPLEX SYSTEMS: AN EXAMPLE: SEAD - UAV SYSTEMS

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FOR THE COMMANDER

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13. ABSTRACT *(Maximum 200 words)*
This investigation evaluates a framework for design of ecological information systems as applied for the command and control function of Unmanned Aerial Vehicle (UAVs). In this context, the term "interface design" is not referring to the human-computer interface, but to the interface between a decision-maker and the deep relational structure of the workspace. This framework was developed for the domains of industrial process and manufacturing systems, tested through analyses of hospital and library systems, and recently further developed to model the socio-technical system involved in risk management in a modern, dynamic society. The introduction of uninhabited vehicles has raised considerable research interest, but the topics discussed have largely been related to the problems appearing when remote control of an air vehicle and its payload is introduced. Correspondingly, the system concept has been described as an effort "to keep the pilots head in the cockpit and leave the rest of him at home" and a literature search has shown that the human factors discussed are related mainly to display, control, and training issues.

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1. Introduction

The aim of the present investigation is an evaluation of the framework for design of ecological information systems as applied for the command and control function of Unmanned Aerial Vehicle (UAVs). In this context, the term "interface design" is not referring to the human-computer interface, but to the interface between a decision maker and the deep relational structure of the work space. This framework was developed for the domains of industrial process and manufacturing systems, tested through analyses of hospital and library systems[1], and recently further developed to model the socio-technical system involved in risk management in a modern, dynamic society.[2]

The introduction of unmanned (more accurately - uninhabited) vehicles has raised considerable research interest, but the topics discussed has largely been related to the problems appearing when remote control of an air vehicle and its payload is introduced.[3] Correspondingly, the system concept has been described[4] as an effort "to keep the pilots head in the cockpit and leave the rest of him at home" and a literature search has shown that the human factors discussed are related mainly to display, control, and training issues.

The discussion is introduced by a brief review of the basic characteristics of UAV systems and their role in military command-and-control, as perceived by military planners. Then the framework for Cognitive Systems Engineering is described and the approach to system analysis and design underlying the framework is compared to the research recommendations of the Air Force Scientific Advisory Board and the characteristics of the system in which UAV command and control is embedded is compared to the socio-technical risk management system to highlight differences in the system phenomena to be modeled.

Following this introduction, the various dimensions of the framework for design of ecological information systems is discussed with special emphasis on UAV systems and their role in SEAD (Suppression of Enemy Air Defense) missions. It became clear at an early phase of the work, that UAV systems

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[1]Rasmussen, J., Pejtersen, A. M. and Goodstein, L. P. (1994): Cognitive Systems Engineering. New York: Wiley.

[2]Rasmussen, J. (1997): Risk management in a Dynamic Society: A Modeling Problem. In: In *Safety Science 27/2-3 (1997), pp. 183-213.*

[3]AGARD Conference on Subsystem Integration for Tactical Missiles (SITM) and Design and Operation of Unmanned Air Vehicles; Ankara, October, 1995.

[4]Col. Michael S. Francis: "Unmanned Tactical Aircraft." op. cit.

should be studied in the wider context of military missions and, as an example, SEAD missions were considered in this report.

2. UAV SYSTEMS

UAV systems have evolved rapidly following the experiences with anti aircraft missiles during the Vietnam war and proven to be very effective for military reconnaissance, surveillance, and target acquisition (RSTA), as well as rapid battle damage assessment (BDA) during the Golf war and the interventions in Bosnia[5]. UAV systems can prevent loss of high-value, manned systems in high-threat or heavily defended areas, they can provide near-real-time and they require relatively few maintenance, control, and operating personnel.

Initially, UAVs were applied mainly for reconnaissance, but presently systems for ballistic missile interception and combat are developed.

Different UAV categories are found having different capabilities:

- The close-range UAV (CR-UAV) category addresses the needs of lower level tactical units for a capability to investigate activities within their area of interest.
- The short-range (SR-UAV) category supports Army divisions, Navy and Air Force combatants, meeting the need to cover enemy activities out to a range of 150 kilometers or more beyond the forward line of own troops. The UAV systems in this category are more sophisticated, can carry a wider variety of payloads and may consist of more than one air vehicle.
- The vertical takeoff and landing UAV (VTOL-UAV) category, designed to complement the SR-UAV inventory with a VTOL-capable vehicle and provide a low cost extension of warship sensors.
- The medium-range UAV (MR-UAV) category addresses the need to provide prestrike and poststrike reconnaissance of heavily defended targets at significant ranges and augment manned reconnaissance platforms by providing high quality, near-real-time imagery. MR-UAV systems will be designed to fly at high subsonic speeds and spend relatively small amounts of time over target areas.
- The endurance UAV (E-UAV) category provides high altitude, heavy payload, multi – purpose missions, and offers support across all mission areas with a flight duration in excess of 24 hours. E-UAV systems will be capable of employing the widest variety of sensors and payloads in support of joint forces.

Illustration of the elements of UAV systems are shown in figures 2.1 and 2.2.

[5] JTTP for Unmanned Aerial Vehicles, JP 3-55.1, 1993. Washington DC.: The Office of the Chairman, The Joint Chiefs of Staff.

The primary mission of UAV units is to provide a commander with near-real-time data on opposing force position, composition, and state of readiness. However, missions may also include:

- Surveillance for search and rescue (peacetime (SAR) and combat (CSAR)).
-Deception operations.
-Maritime operations, such as:
    Naval surface fire support (NSFS).
    Over-the-horizon targeting (OTH-T).
    Ship classification.
    Antiship missile defense (ASMD).
    Antisubmarine warfare (ASW).
    Search and rescue (SAR).
    Mine defense support.
- Electronic warfare (EW) (including electronic attack (EA)), signals intelligence (SIGINT), and directed energy sensor reconnaissance.
- Nuclear, biological, and chemical (NBC) reconnaissance.
- Special and psychological operations:
- Re-supply for special operations and psychological operations teams (scheduled and emergency).
- Leaflet delivery and broadcast.
- Meteorology missions.
- Route and landing zone reconnaissance support.
- Adjustment of indirect fires and close air support (CAS).
- Rear area security support.
- Radio and data relay.

This list has recently been extended with a number of more civilian and humanitarian missions, see table 2.1.

This brief review demonstrates that several different UAV systems with different operational characteristics are found, and that they will serve within many different mission contexts.

Their potential impact on the organizational command-and control structure they are embedded in has been widely discussed by theorists from several military branches. Considering the role of UAV systems to be a link in the general RSTA activity in the battle space, a review of the present development in the context of Marine Expeditionary Forces[6] illustrates the organizational importance of UAV systems and supports the claim that a cognitive systems engineering approach will be useful for analysis of the impact of UAV systems on the structure of military C4I and their influence upon mission planning and coordination.

The review defines the situation as follows:

> "The emerging body of Reconnaissance, Surveillance, and Targeting Acquisition (RSTA) resources brings a powerful contribution to battlespace domination. Diverse RSTA operations occur simultaneously within the battlespace--keyed to support a range of users from decision makers to "shooters." In addition to collecting information that develops situational awareness, RSTA assets contribute to many battle space activities: Intelligence Preparation of the Battlespace, Indications and Warning, situation development, force protection, Battle Damage Assessment, targeting and collection queuing. Given this multi-dimensional capability, it is no longer desirable to relegate RSTA assets solely to the realm of intelligence collection management. The command and control of finite, high value RSTA resources is the Commander's responsibility, one demanding top-down planning and unity of effort throughout the MAGTF to achieve a synchronized intelligence-operations approach to RSTA employment."

Furthermore, the functions involve a complex system of decision makers in a cooperation which change with the problem situation and are under increasing time stress:

> "Not surprisingly, synchronizing diverse RSTA capabilities to support operations involves complex coordination and planning considerations. During this process, the Commander and his staff must ask themselves: Are these assets best employed in general support of the MAGTF [i.e., Marine Group Task Force], direct support of subordinate units, or both? Will these assets fall under G2 or G3 purview, or should a Commander-designated board conduct oversight and management? What relationship must be established, what coordination effected between organic and non organic RSTA assets and the Surveillance and Reconnaissance Center (SARC), the Combat Intelligence Center (CIC), and the Combat Operations Center (COC)? Who orchestrates the coordination for RSTA planning, and who provides the sanity check on how well the collection strategy supports operations? Given that diverse RSTA operations occur simultaneously within the battlespace--keyed to support a range of users from decision makers to "shooters"--what parameters must define the information flow, and who should oversee the dissemination process to ensure usable intelligence reaches the Major Subordinate Commands?"

On this background, the report identifies a dilemma in this way:

> "As the spectrum of battlefield systems becomes more sophisticated and diverse, intelligence requirements to support battlefield operations grow astronomically--from collecting on and correlating battlefield activities to developing target packages; from analyzing Battle Damage Assessment (BDA) to

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[6]Source: Reconnaissance, Surveillance, and Target Acquisition Collection Planning--Embedded Within the MEF Intelligence and Operations Cycles.
By: Intelligence Doctrine Working Group; May 1995; Chairman: Major J.C. Dereschuk, United States Marine Corps (www.clark.net/fas/irp/eprint/derescheck.htm).

relaying information in near-real-time (NRT) to a tactical commander. (1) General Clapper, Director of DIA, recently commented on these demands placed on intelligence: As a result, intelligence simply must situate itself within the operational cycle rather than outside it...the intelligence collection, production and dissemination cycle must be compressed so that it fits within the operational cycle for targeting to support strike and restrike operations. (2)."

The report on MEF Intelligence and Operations explicitly points to the need of an analysis in terms of distributed, high-tempo, collaborative decision making with a potential for fast horizontal communication among 'viewers' and 'shooters' at the same time as vertical exchange of factual information (targets and battle assessment) and intentional information (plans and COAs) is supported.

In this context, UAV systems have multiple functions within military missions, see table 1. The context within which the elementary UAV and payload control tasks are integrated consequently vary widely with the situation, and a framework for design and evaluation which capture the necessary adaptive abilities of the system is necessary. This appears to be an important support of the use of a cognitive engineering perspective in place of a classic task analysis.

The UAV systems will be described in more detail with reference to the Cognitive Systems Engineering framework in subsequent sections. To give a background for this discussion, the brief review of the frame work and its origin as found in the next section will be useful.

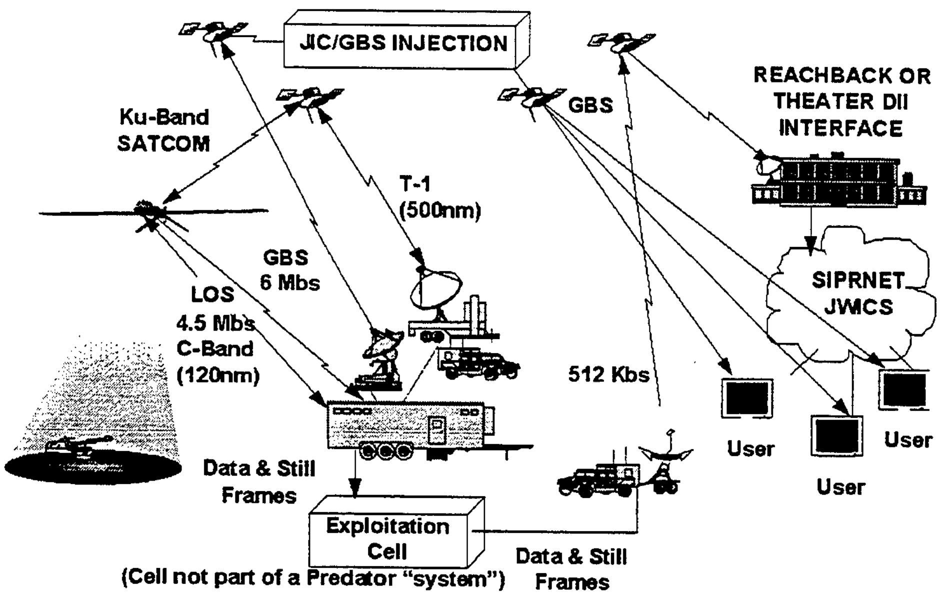

Figure 2.1 The Predator UAV system[7]

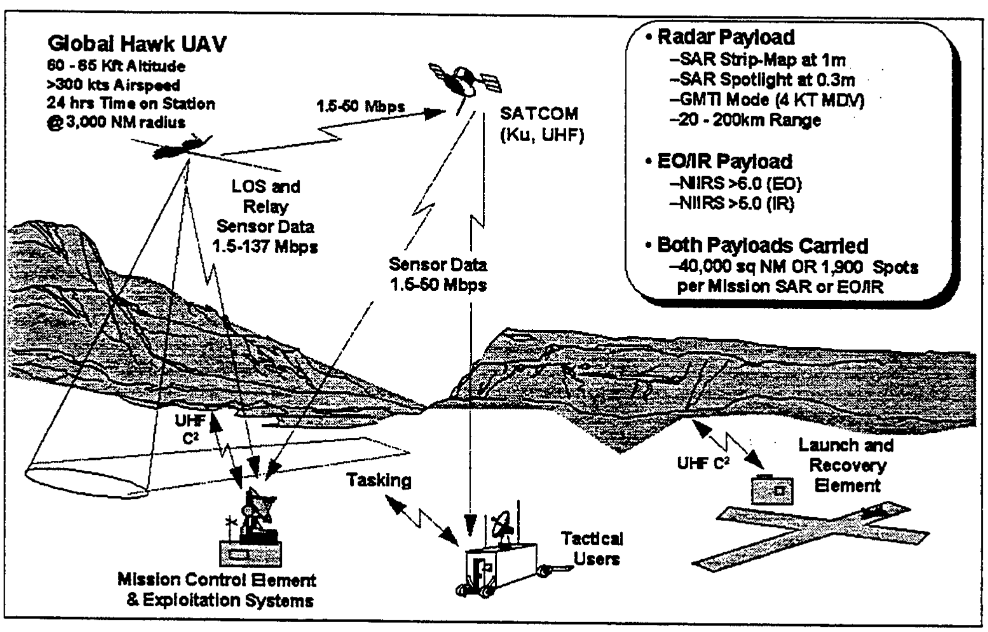

Figure 2.2 The Global Hawk split-site concept

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7 Source of Figs. 2.1 and 2.2: Air Combat Command Concepts of Operations for Endurance Unmanned Aerial Vehicles; December 1996, Version 2. Downloaded from Federation of American Scientists, DoD Conops File Series

Potential Applications for UAV Systems

- Near- Real -Time (NRT) Targeting and Precision Strike Support
- NRT Combat Assessment
- Enemy Order of Battle (EOB) Information
- Battle Damage Assessment (BDA)
- Special Operations
- Blockade and Quarantine Enforcement
- Sensitive Reconnaissance Operations
- Humanitarian Aid Missions
- United Nations (UN) Treaty Monitoring
- Counter Drugs Missions
- Single Integrated Operational Plan (SIOP)
- Communications

Table 2.1. Potential applications of UAV systems (example[8] is for endurance UAVs).

[8]Air Combat Command Concepts of Operations for Endurance Unmanned Aerial Vehicles; December 1996, Version 2. Downloaded from Federation of American Scientists, DoD Conops File Series.

3. EID: Ecological Interface Design

Modern human-machine systems have evolved by incremental improvement in response to technological innovations, such as new interface technology, and to operational experience, such as accidents. With respect to design of interfaces serving the control of technical systems, such as e.g., industrial process plants, an evolution is found from the traditional one-sensor-one-indicator concept typically designed by the equipment supplier, over computer-based graphic displays mimicking the traditional interfaces, toward a more integrated interface design including display formats based on integration of data into higher level information matching task requirements. Still, however, interface design often appears to be an add-on by human factors and/or computer specialists following design of the technical core.

The same picture is found within aviation. Interface guidelines for 'user-centered design' are typically organized according to equipment categories and functions,[9] interfaces are organized subsequent to the equipment design by human factors experts, and the aim is to match them to the users' performance modes and mental models.

Such an incremental up-date of system design in response to technical innovations and operational problems becomes inadequate when basic changes in system technology appear. Considering the very fast and concurrent pace of change of technologies such as combat UAVs, GPS systems, and sensors, we are facing a multidimensional change of basic system parameters, and the performance of the new system cannot be evaluated from an integration of part models developed separately. In addition to the local optimization of system elements, a system oriented evaluation of the overall adaptation to these changes is mandatory. Following a significant change of technology, a new operational optimum is to be expected at a different location in the multidimensional performance space, see figure 3.1, and a quantum leap in several dimensions of design parameters should be considered, based on a predictive model of system performance. It is to support this kind of analyses, the cognitive systems engineering methods[10] have evolved during the later decades.

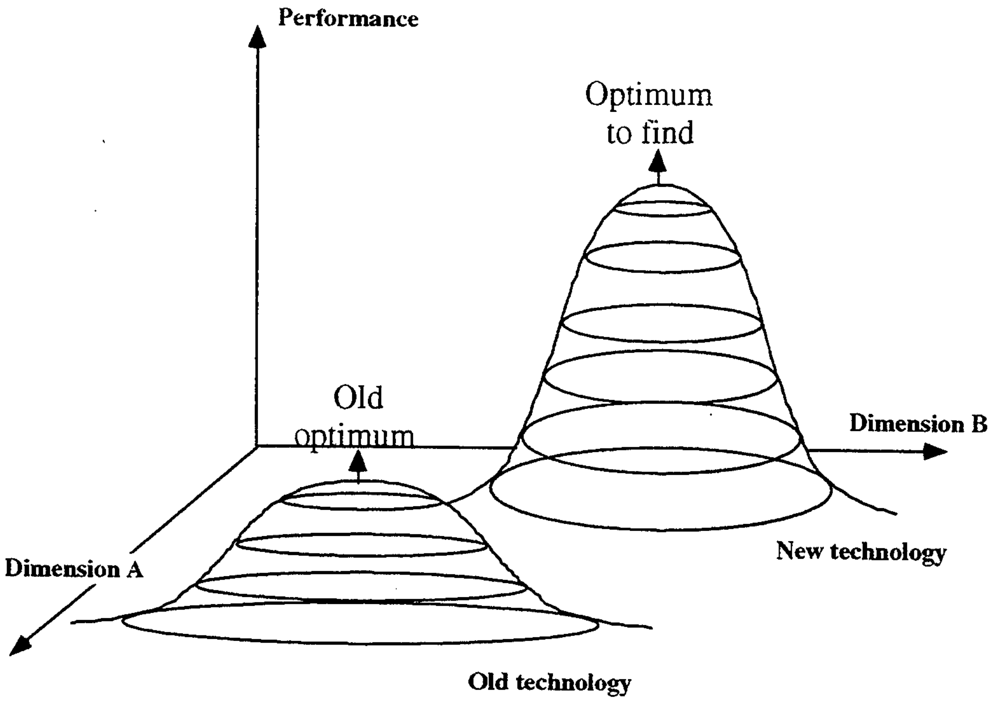
[9]see e. g., Billings, Ch. E. (1991): Human-Centered Aircraft Automation: A Concept and Guidelines. NASA Tech. Memo. 102885. Moffett Field, Ca.: Ames Research Center.

[10]For the approach underlying the present discussion, see Rasmussen, J., Pejtersen, A. M. and Goodstein, L. P. (1994): Cognitive Systems Engineering. New York: Wiley.

Another important aspect of modern, dynamic work systems is the need for a modeling framework that can capture the *adaptive nature of work performance.* Work systems are traditionally modeled by decomposition into structural elements, such as equipment, operators, human-machine interfaces, management, etc., and the *dynamic behavior of systems and actors* is modeled by decomposition of the behavioral flow into events. Such decomposition is the basis for identification of activity elements in terms of tasks and in task elements in terms of decisions, acts, and errors. A basic problem is that modern work situations leave many degrees of freedom to the actors for choice of means and time for action even when the objectives of work are being fulfilled. Consequently, a task instruction or standard operating procedure in terms of a sequence of acts cannot be used as a reference of judging behavior nor as the basis for interface design. To describe behavior as a sequence of acts in a task, the open degrees of freedom must be resolved by assuming additional performance criteria that appear to be 'rational' to work planners and human factors analysts. They cannot, however, foresee all local contingencies of the work context and, in particular, a rule or instruction is often designed separately for a particular task in isolation whereas, in the actual situation, several tasks are active in a time sharing mode. This situation poses additional constraints on the procedure to use, which cannot be known by a system designer or work planner.

This has very basic implications for modeling performance in a dynamic work space. Modeling is not focused on task analysis and study of user's mental models, but on the features of the work space that shape individual and organizational behavior through adaptation to system properties and response to changes. Similarly, design cannot be based on responses to errors and accidents in the past but should be oriented toward creation of a work interface that will serve to create proper mental models during the adaptation that will take place guided by the situational criteria and by the users' subjective preferences.

Two aspects of adaptation must be explicitly taken into account. One is the *adaptation of the individual* to the local work space, another one is the *dynamic adaptation of the organization* to changing technology and to environmental pressure, that is, the changing *division of work* resulting from organizational adaptation to the control requirements of the work space. This latter aspect implies that the organization of the total socio-technical system cannot be decomposed into separate levels such as technical core, operation, and management to be studied separately by different research disciplines.



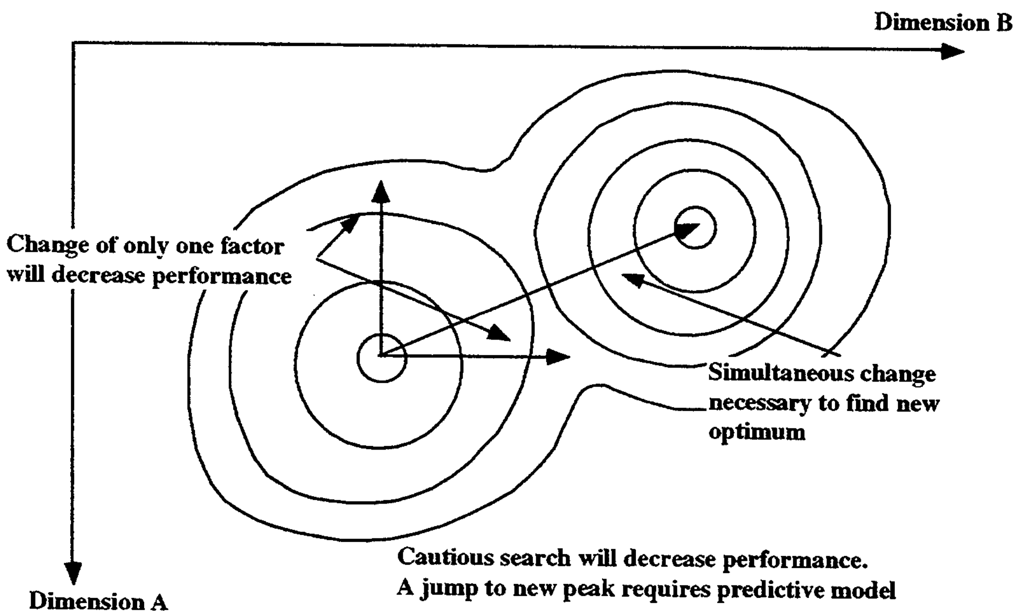


Figure 3.1. Design in a multi-dimensional specification space - in this case two-dimensional. A missing consideration of only one dimension may cause an otherwise optimal design to fail.

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4. An Example: Industrial Risk Management

The present need for this modeling approach has been confirmed by analyses of industrial accident causation and risk management. Reviews of accidents invariably conclude that some 80% of the cases are caused by human error and great effort is spent to improve safety by better training schemes, by safety campaigns motivating the work force to be safety conscious, and by improved work system design. However, low risk operation of modern, high hazard system normally depends on several lines of defenses against the effects of faults and errors and the analysis of recent major accidents have also shown[11] that they are not caused by a stochastic coincidence of faults and human errors, but by a systemic erosion of the defenses. In other words, improvement of the safety of high hazard installations involves an improvement of systemic factors affecting system management rather than attempts to control the individual human errors.

Injuries, contamination of environment, and loss of investment all depend on loss of control of a physical processes capable of injuring people or damaging property. The propagation of an accidental course of events is shaped by the activity of people which either can trigger an accidental flow of events or divert a normal flow. Safety, then, depends on the control of work processes so as to avoid accidental side effects causing harm to people, environment, or investment.

Many levels of politicians, managers, safety officers, and work planners are involved in the control of safety by means of laws, rules, and instructions that are verbal means for the ultimate control of some hazardous, physical process. They seek to motivate workers and operators, to educate them, to guide them, or to constrain their behavior by rules, so as to increase the safety of their performance, see figure 4.1.

Compared to the stable conditions of the past, the present dynamic society brings with it some dramatic changes of the conditions of industrial risk management:

- A very fast pace of change of technology is found at the operative level of society within all domains, such as transport, shipping, manufacturing

[11] Rasmussen, J. (1993): Market Economy, Management Culture and Accident Causation: New Research Issues? Proceedings Second International Conference on Safety Science. Budapest: Meeting Budapest Organizer Ltd.

Rasmussen, J. (1994): Risk Management, Adaptation, and Design for Safety. In: Sahlin, N. E. and B. Brehmer (Eds.): Future Risks and Risk management. Dordrecht: Kluwer. 1994.

and process industry. This pace of change is much faster than the pace of change presently found in management structures and in legislation and regulation. In consequence, a problem is found in the different time constants of change at the different levels of society. The dynamic interaction among the various levels during a period of change thus becomes an important modeling problem.

- The scale of industrial installations is steadily increasing with a corresponding potential for large-scale accidents and very low probabilities of accidents have to be demonstrated for acceptance of operation by society. Consequently, models should not only include the normal or average performance but the performance also during very rare conditions.
- The development of information technology, effective transport systems, and just-in-time production schemes lead to a high degree of integration and coupling of systems and effects of a single decision can have dramatic effects that propagate rapidly and widely through the global society. It is thus becoming increasingly difficult to model systems in isolation and to make small-scale, local experiments to evaluate models.
- Furthermore, companies today live in a very aggressive and competitive environment which will focus the incentives of decision makers on short term financial criteria rather than long term criteria concerning welfare, safety, and environmental impact.

In this situation, it should be considered that commercial success in a competitive environment implies exploitation of the benefit from operating at the fringes of the usual, accepted practice. Closing in on and exploring the boundaries of normal and functionally acceptable boundaries of established practice during critical situations necessarily imply the risk of crossing the limits of safe practices. As already mentioned, court reports from several accidents such as Bhopal, Flixborough, Zeebrügge, and Chernobyl demonstrate that they have been caused by a systematic migration of organizational behavior toward accident under the influence of pressure toward cost-effectiveness in an aggressive, competitive environment.[12]

When this systemic migration toward accident is taking place, the interaction among the decision makers potentially involved in accident causation at the various levels of the socio-technical system has some very special features. All these decision makers are busy managing their particular work space and their attention will be focused on the control of the means and ends of their normal productive tasks while they strive to meet their production targets, often under

[12]Op. cit. Previous page.

considerable stress to optimize process criteria such as time spent and cost-effectiveness. This must be done while respecting the constraint defined for their local context, including the boundaries defining safe overall operation. A critical issue is that the boundaries relevant to a particular decision maker depend on the activities of several other decision makers found within the total system and that *accidents are created by the interaction of potential side effects of the performance of several decision makers during their normal work.*

In conclusion, in a dynamic society system analyses to serve design of work support systems cannot be focused on task analysis and efforts to match interfaces to users' mental models. Instead, efforts must be directed toward an identification of the space of action opportunities, that is, the degrees of freedom open for users, and toward design of support systems that make visible to the user the relational (functional) structure of the work space, the opportunities for action, and the boundaries of acceptable system function.

As we will see below, the mission context of SEAD operations have characteristics very similar those of risk industrial risk management in a dynamic society, and the Cognitive Systems Engineering approach to analysis should transfer directly to the SEAD domain .

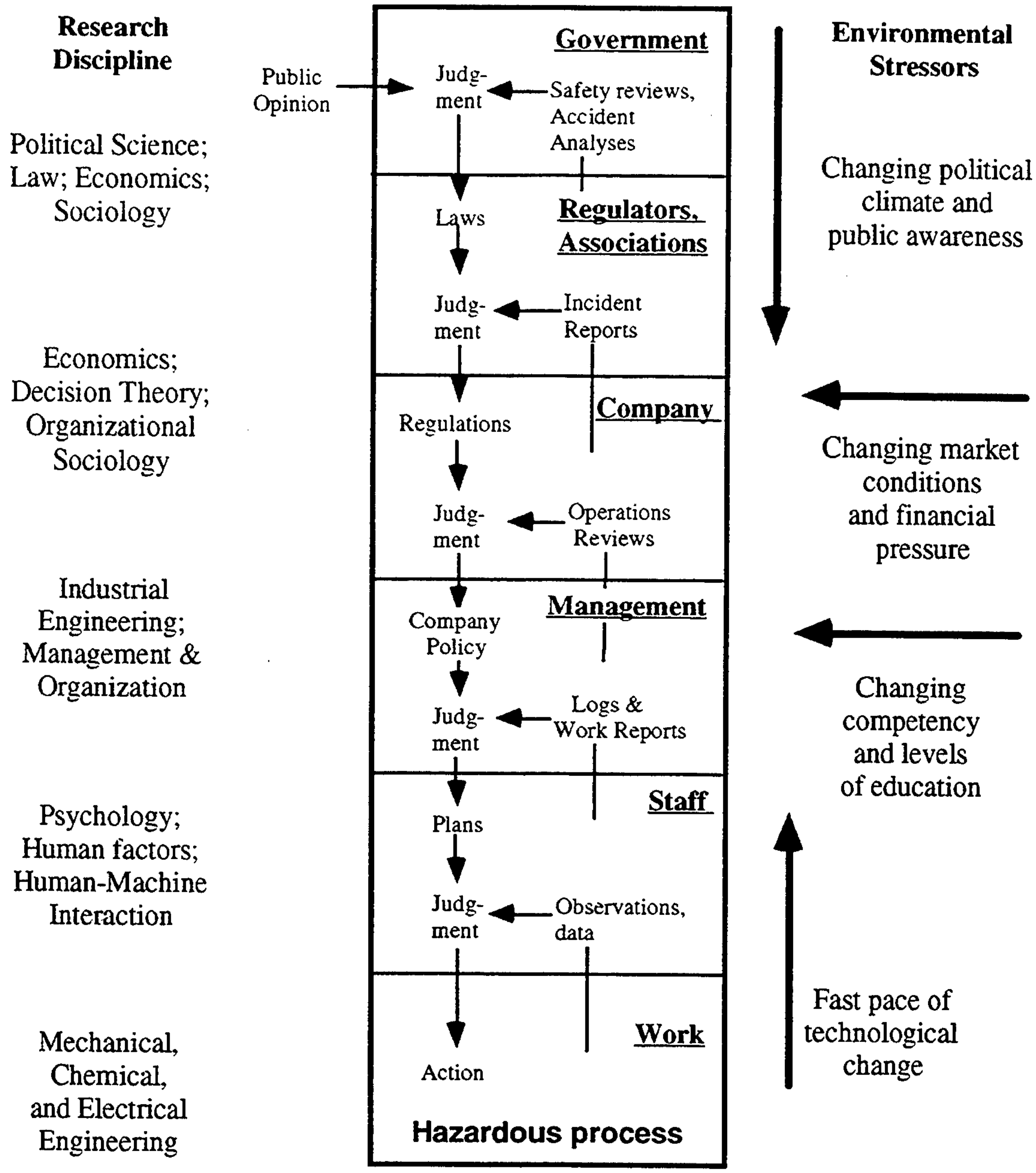

Figure 4.1. The socio-technical system involved in risk management.

5. Air Force Research Needs and Cognitive Systems Engineering

This section reviews the present Airforce research needs as recently stated by the Air Force Scientific Advisory Board and compares to the characteristics of the Cognitive Systems Engineering framework.

5.1 Vision of the Air Force Scientific Advisory Board

The relevance for the Air Force needs of this framework for modeling adaptive organizations can be judged with reference to the recommendations of the Scientific Advisory Board.[13]

The board has presented a "Vision of Aerospace Command and Control for the 21st Century by evaluating the current state of C2 and developing a migration strategy and process improvements that will allow movement from the current status toward that Vision.

5.1.1 Command and Control Philosophy

In the recommendations, command and control is defined as the act of leading and directing the resources assigned to a military commander and emphasis is on the influence of the present national and global situation that place unprecedented demand on C2 and the systems that support it. Quote:

> The end of the Cold War has left the US military with an enormous challenge of adaptation. That challenge derives from several conditions outlined below.
>
> - The decreased military strength of the former Soviet Bloc and the victory in Desert Storm present a "post war" climate in Congress and the populace that expects a smaller, less costly military force.
> - Being the only global superpower means that the number of instances in which US forces might be called into play actually increases over that experienced during the Cold War.
> - With such global responsibility, the smaller force must still reach anywhere, anytime, and more likely, from bases within CONUS.
> - The type and degree of hostilities now range wider than ever—from major regional conflicts to large, sometimes threatening, humanitarian missions.
> - An increase in the use of small insurgent, guerrilla, and terrorist forms of warfare, plus the availability of small but very lethal weapons, require an increasing need for rapid and precise response.
> - The political and economic interests on which US forces may act are less predictable.

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13 *Vision of Aerospace Command and Control For the 21st Century,* Executive Summary; SAB-TR-96-02ES.

5.1.2 Research Needs

This command and control philosophy implies that the Air Force must cope with a wide range of missions, military as well as humanitarian, dispersed over the globe, requiring fast response but with fewer resources. This is an extraordinary challenge which can only be met by an integrated and responsive C2 support system. The 'vision' suggests how an increased understanding of the battle space and a vastly electronic integration of resources can meet this challenge:

The factors and conditions considered are summarized in this way:

- The shrinking DoD budget and changes in US military strategy are resulting in a largely CONUS-based force. At the same time though, the sphere of US interests continues to expand.
- Joint and coalition operations will be the norm, not the exception.
- Many operations may be simultaneous and widely dispersed geographically. In these situations, interoperability will be essential, particularly C2 interoperability.
- Regional access to facilities and communications may not be easy or at least as extensive as that available in CONUS. The infrastructure available to support operations may be limited. This is further complicated by the need for smaller forward deployments. The C2 system must be modular to enable tailoring for specific use with a minimum logistics footprint.
- The ability to understand what is occurring in the battle space has made the Air Force aware of C2-imposed limitations on combat effectiveness. As a consequence, the true potential of aerospace power has not been completely realized.
- Aerospace power will be called upon to rapidly move military equipment, people, and supplies worldwide. Missions will range from isolating the battlefield in one part of the world and providing information to forces in another. At the same time, aerospace power must be prepared to fight a major regional conflict anywhere in the world.
- Aerospace power will be the option of choice for many dimensions of conflict.
- The development and procurement of an agile, affordable C2 system to support future operations depends on the Air Force's ability to easily and routinely incorporate commercial technology. The current Air Force requirements and acquisition process is not fast or flexible enough to permit this routinely—change is needed.

These conditions have made the inefficiencies and cost of the current C2 systems intolerable; in fact, aerospace power is seriously handicapped by today's C2 system. The power of precision weapon delivery and target attack and the ability to respond rapidly to and in any contingency are all inhibited to varying degrees today. Aerospace C2 for the next century must be designed to remove these shackles in order to unleash the total capability that aerospace power possesses.

From here, it is concluded that to support the Joint Task Force Commander's needs, the C2 systems must have the following attributes and capabilities:

- Enhanced decision making tools which enable the decision maker to solve multi-dimensional, time-sensitive problems.
- Increased efficiency by allowing the operator to accomplish the task better, quicker, and with fewer mistakes by,
  - providing information to the decision maker sooner,
  - allowing Commanders to operate from the same knowledge base for common understanding of the battle space situation,
  - making information available, through integration, interoperability, and tailorable releaseability to all operators for improved mission success,
  - allowing flexibility to employ aerospace power across varying conflicts and differing levels of delegated authority,
  - tailoring the information for mission and resource needs (rapid deployability enables split base operations),
  - allowing the use of existing commercial infrastructures, where logical and reliable,
  - allowing "plug and play" capability for quick and effective response to any operation,
  - allowing for decisions based on a mission to task relationship, not a technology relationship.

These conclusions of the Air Force Scientific Advisory Board reflect a problem context and external stresses very similar to the situation found in industrial risk management in the present dynamic society. We are considering a complex, socio-technical system including the government policy at the top level, the various goal setting and coordinating bodies at several intermediate levels and the operation of physical resources at the bottom, and a map of the military command and control system can be drawn which is very similar to the industrial risk management system. An attempt to draw such a map is shown in figure 5.1 and the system involved in planning major endurance UAV missions are shown in figure 5.2.

5.2 Military Command and Control versus Risk Management

From this comparison, it appears that the socio-technical systems involved in industrial risk management and in military command-and-control have many similar characteristics and are both exposed to bottom-up stress from a fast pace of technological change, to top-down influence from political changes of objectives and strategies, and to side-wards pressure from public opinion and changing operational environments. A transfer of the ecological modeling approach as a basis for design of command-and-control systems will be realistic. There are, however, some basic differences in the problem space that must be explicitly considered when transferring the modeling framework.

In focus of the modeling efforts for industrial risk management is an organization and its activities aimed at the control of its technical resources according to the commercial objectives and within the boundaries of safe operation. The competitive nature of business has only been considered in terms of pressure on the resources available for safety measures, and the gaming nature of business strategies thus have not been explicitly included in the risk management modeling. In other words, management control strategies as modeled have been focused on control of the technical core and disturbances propagating bottom up from changes introduced and faults originating in the technical system. That is, the focus of diagnostic situation analysis is on *causal* relationships.

This is not the case for a military system involved in SEAD missions and control of UAV systems, here the game aspect of operations will have to be explicitly modeled. While the military organization considered is doing its best to control its technical resources according to system objectives, the enemy will strive hard to interfere by changing the problem space. In this case, the diagnostic aspect of situation analysis to a large extent will be *intentional*, that is, a major aim of situation analysis will be to identify the intent of the opponent and predict his actions.

This aspect of military command and control systems is well captured by the proposed ecological modeling framework, because the problem space representation includes intentional as well as causal constraints.

Furthermore, if an organization has a stable technical core, standard practices will evolve and degrees of freedom left out of consideration and forgotten. This is the situation when task analysis and standard human factors apply well. In a highly dynamic, game environment, it is important to maintain all degrees of freedom open and active, and this is in particular the case when faced with an aggressive opponent seeking unusual ways to interfere. Also in this situation, the proposed modeling approach is suitable, with its focus on representation of constraints and action opportunities rather than on task analysis.

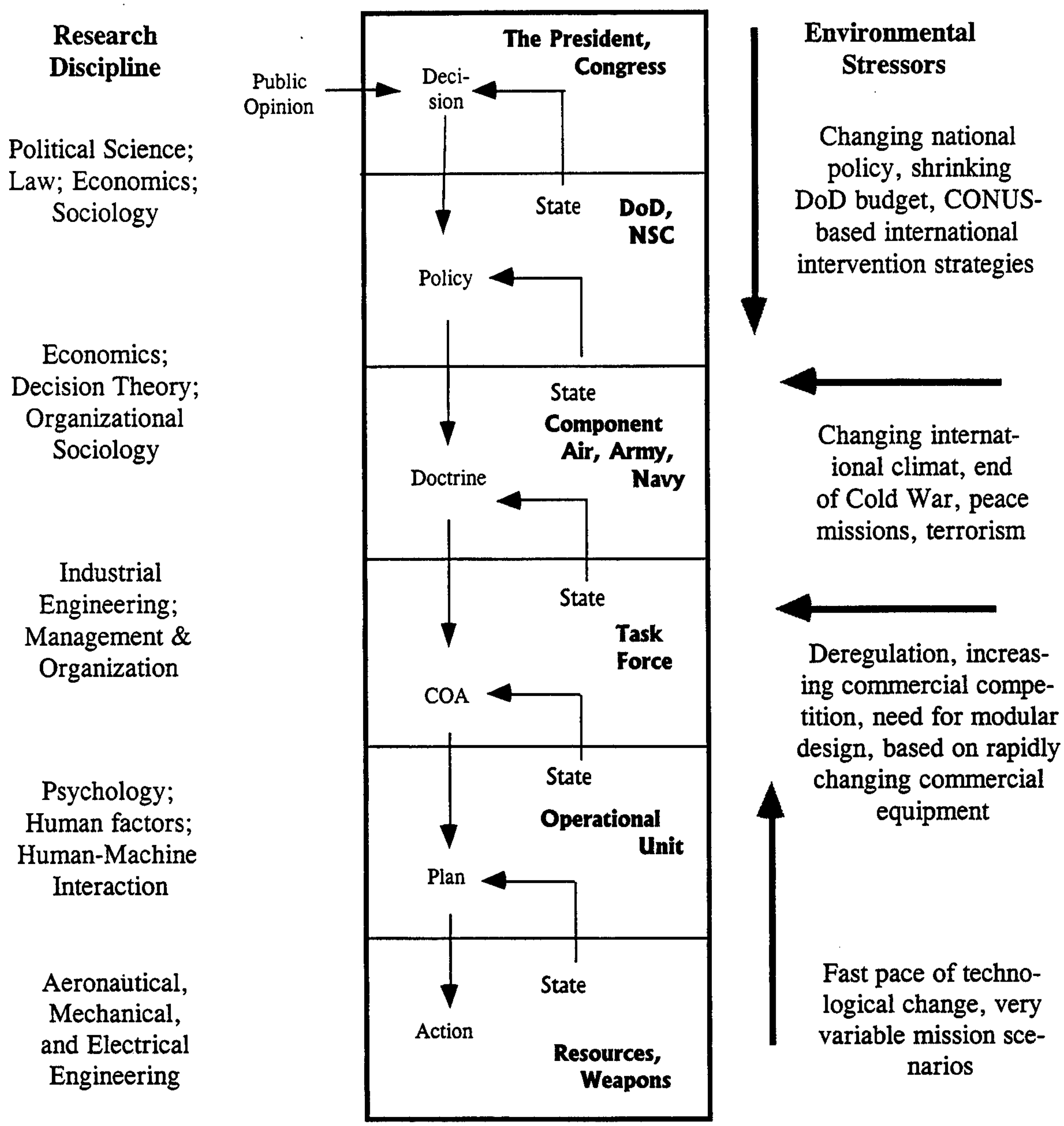

Figure 5.1. A complex, socio-technical system is active in the control of military, operational systems. This social organization is subject to pressure: it operates in a dynamic world, a fast pace of technological change from the bottom meet slow responses at the higher, political levels. Effective operation depends on proper co-ordination of decision making at all levels that constitutes the control structure for the physical operations at the bottom. Analysis of system function requires a study of *the vertical interaction* of performance. However, each of the levels are often studied separately in studies generalizing *horizontally across systems* within different research disciplines.

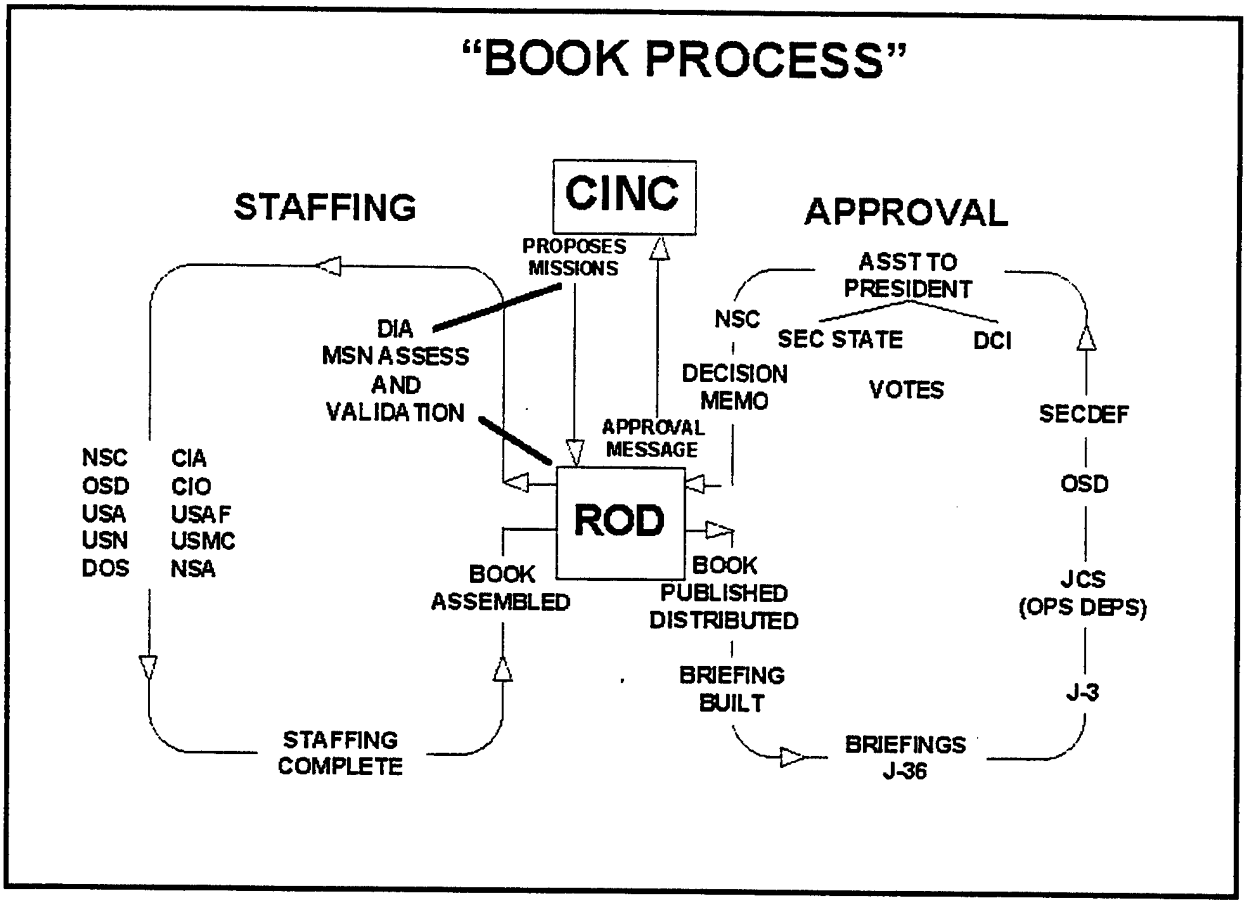

Figure 5.2. The "Book-Process" for approval of major endurance UAV Missions.[14]

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[14]Reproduced from: Air Combat Command Concepts of Operations for Endurance Unmanned Aerial Vehicles; December 1996, Version 2. Downloaded from Federation of American Scientists, DoD Conops File Series.

6. Modeling Adaptive Work Systems

It follows from the discussion above that the UAV operation within a SEAD context depends on a command-and-control organization that is capable to adapt dynamically to the requirements of very varying operational conditions. The fundamental design issue then is not to match decision support systems to preplanned procedures and courses of action (COAs), nor to up-date existing systems to fight the causes of problems experienced in the past. The design must serve to create a work environment that support the navigation of decision makers and actors in a complex, changing problem space. The support system should make the deep relational structure of the problem space visible to actors, identify the options for action and indicate the boundaries of successful performance. For a command-and-control organization faced with a dynamic and competitive environment and a fast pace of technological change, this is very likely the only effective way to ensure a long term effectiveness of a particular design of decision support systems. A closer look at this question is important for the discussion of reliable design of systems subject to pressure from a dynamic environment.

6.1. Task vs. Work Analysis

Routine operation of stable and well-structured technical equipment depends on repetitive and rather stable tasks. In this case, *'task analyses'* are the basis of design. The technical part of the system is analyzed with respect to the necessary control sequences, an operating procedure is then issued to guide operators, and an interface is designed so as to present the information necessary to cue the actions of the procedural sequence. A subsequent human factors evaluation and a test period serve to prove that the system *can* be operated that way, and later failures to do so are then taken to be 'operator errors.'

However, most modern work systems leave many degrees of freedom to the actors even if behavior during work, by definition, is oriented towards the requirements of the system. Functional objectives, that is, *what* should be done, can be well defined, whereas *when* and *how* to accomplish those objectives often leave some options open. This is clearly the case for UAV systems. In this case, design depends on a *work analysis* serving to identify the work space within which actors are free to navigate and the options for action from which they can choose.

The options from which to chose will depend on the actual operational conditions and will be defined by the system resources which create a space of possibilities for the operators within an envelope defined by the limits of functionally acceptable work performance, by limits of acceptable cost-effectiveness and, finally, by the work load acceptable to the individual. Within this space of acceptable work performance, many degrees of freedom are still left for the individual to choose among strategies and to implement them in particular sequences of behavior. This freedom will be used by an actor to shift among possible strategies to match resources to local conditions (with respect to time or information available, to mental processing or memory limitations, etc.) and to optimize performance with respect to subjective performance criteria (such as cost-effectiveness, cognitive strain, cost of failure, joy of discovery, etc.).

The actors' response to situational and subjective factors when closing the space of opportunities results in a variability of performance that can be illustrated by a space of 'Brownian movements' around the normal performance (see figure 6.1) and gives performance a somewhat stochastic appearance. This space of fluctuating performance, embedded in a larger space of acceptable performance, is subject to gradients such as the pressure from management toward improved cost-effectiveness and the individual preference for the path of least resistance. From this follows by a thermo-dynamic analogy a natural migration toward the limits of acceptable performance. Sooner or later, performance will reach the limit and a system failure will be the result.

This very adaptive behavior of actors in a human-machine system points to the need for modeling behavior at a higher level of abstraction than the usual modeling in terms of sequences of events, decisions, acts, and errors. A comparison can be made to the two levels of modeling in physics, the thermo-dynamic models in terms of fields and gradients, and the classic models of particle physics.

It follows from this discussion that the design of new work support systems should be focused on creation of an interface between decision makers and the functional structure of the work space defined by operational and basic resource constraints. Within this space the actors should be allowed to adapt freely according to situation dependent and subjective criteria. This is the basic idea behind the "Ecological Interface Design" concepts as embedded in the Cognitive Systems Engineering design approach.[15]

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[15]For the design approach promoted in the present context, see: Rasmussen, J., Pejtersen, A. M. and Goodstein, L. P. (1994): *Cognitive Systems Engineering.* New York: Wiley.

6.2. Systems Analysis for Design

A 'Cognitive Systems Engineering' framework is aimed at the design of work support systems and interfaces. The framework considered here includes two concurrent analysis of work and work performance, see figure 6.2. One analysis shown in the upper path serves to identify the constraints and action opportunities of actors in different representational languages, another shown in the lower path, serves an analysis of the organizational adaptation to work requirements and the identification of the role and characteristics of the individual agent. Figure 6.3 reviews the content of the different dimensions of analysis with reference to the numbers in figure 6.2.

6.3. Modeling of Activities

This line of analysis is concerned with the work requirements, constraints and degrees of freedom which are to be compared to the agent's resources and preferences in order to determine the individual actor's likely choice of performance. The degrees of freedom are represented by a repertoire of 'possible' formulations of tasks and strategies that *can* be used by an agent. To judge which strategy an actor *will* use, the criteria underlying local and subjective interpretations must be known.

The analysis must serve to represent the characteristics of both the physical work environment and the 'situational' interpretation of this environment by the actors involved, depending on their skills and values. In order to bridge from a description of the behavior shaping constraints in work domain terms to a description of human resource profiles and subjective preferences, several different *perspectives of analysis* and *languages of representation* are necessary, see figure 6.4.

It will be necessary to adopt an economic strategy of analysis, that is, one which converges rapidly by eliminating the degrees of freedom in the sets of behavior shaping constraints represented within the different dimensions:

1) First, a topographic delimitation of the work space should be found and an explicit identification of the goals, constraints, and means for action which are available to an actor in terms of a *means-ends hierarchy.*
2) A delimitation in time to determine the *task situation* will be made, followed by
3) a delimitation and shift in representation language to describe the *decision task.* The following step then involves a focus on
4) the mental activities in terms of the mental strategies that can be applied for the task. This implies a related shift in language, in order to have a

description compatible with a representation of the actor's cognitive resource profile and performance criteria.

This framework supports a stepwise narrowing down of the degrees of freedom faced by an actor and, in addition, the necessary shifts in language of description when going from the context of the work domain, the task situation, the decision and information processing task, onto human cognitive and emotional factors.

6.4. Modeling Division of Work

The lower line of analysis in figure 6.2 is aimed at a description of the role, the resource profile, and the subjective preferences of the individual agents and an identification of the cooperative structure. The work domain is considered a loosely coupled work system controlled by the distributed decision making of cooperating agents. The analysis is focused on a determination of the criteria that control the dynamic distribution of work, that is, the role allocation, and the content of the communication necessary for concerted action. In addition, the preferred form of communication as influenced by the adopted management style, is analyzed.

6.5. Displays and Information Windows

In conclusion, one line of analysis serve to represent activities by an increasingly detailed identification of behavior-shaping constraints ending by identification of the mental strategies that are at the actors disposal and should be supported. This analysis thus guides the design of displays serving the individual decision tasks. Another line of analysis serve to describe the constraints and criteria dynamically shaping the division of work and thus to guide the determination of the information window the should be open to an actor during a particular work situation. The two lines of analysis will clearly require continuous iteration during a system analysis.

In the subsequent sections, the dimensions of analysis are described in detail with reference to one frequent operational context of UAV operations: a SEAD - Suppression of Enemy Air Defense - mission.

6.6. Modeling the Context of UAV Operation: A SEAD System

The application of the various dimensions of analysis will be discussed in the subsequent sections taking an SEAD system as the problem space. The scope of the analysis is extended from the initial focus on a UAV system because introduction of UAVs together with several other technical innovations can be expected to change the command and control system for the entire SEAD mission. The discussion will be organized according to the phases of analyses shown in figure 6.2, beginning with an analysis of activities as shown in the upper path of analysis.

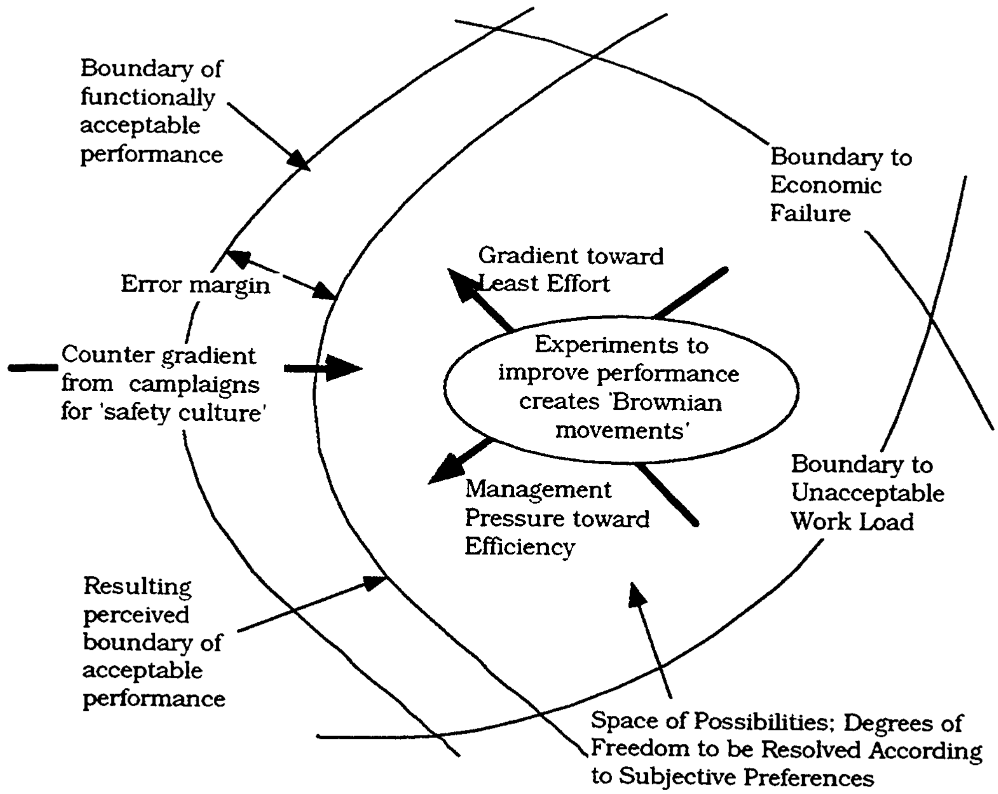

Figure 6.1. The actors' response to situational and subjective factors when closing the space of opportunities results in a variability of performance that can be illustrated by a space of 'Brownian movements' around the normal performance and gives performance a somewhat stochastic appearance. This space of fluctuating performance, embedded in a larger space of acceptable performance, is subject to gradients such as the pressure from management toward improved cost-effectiveness and the individual preference for the path of least resistance.

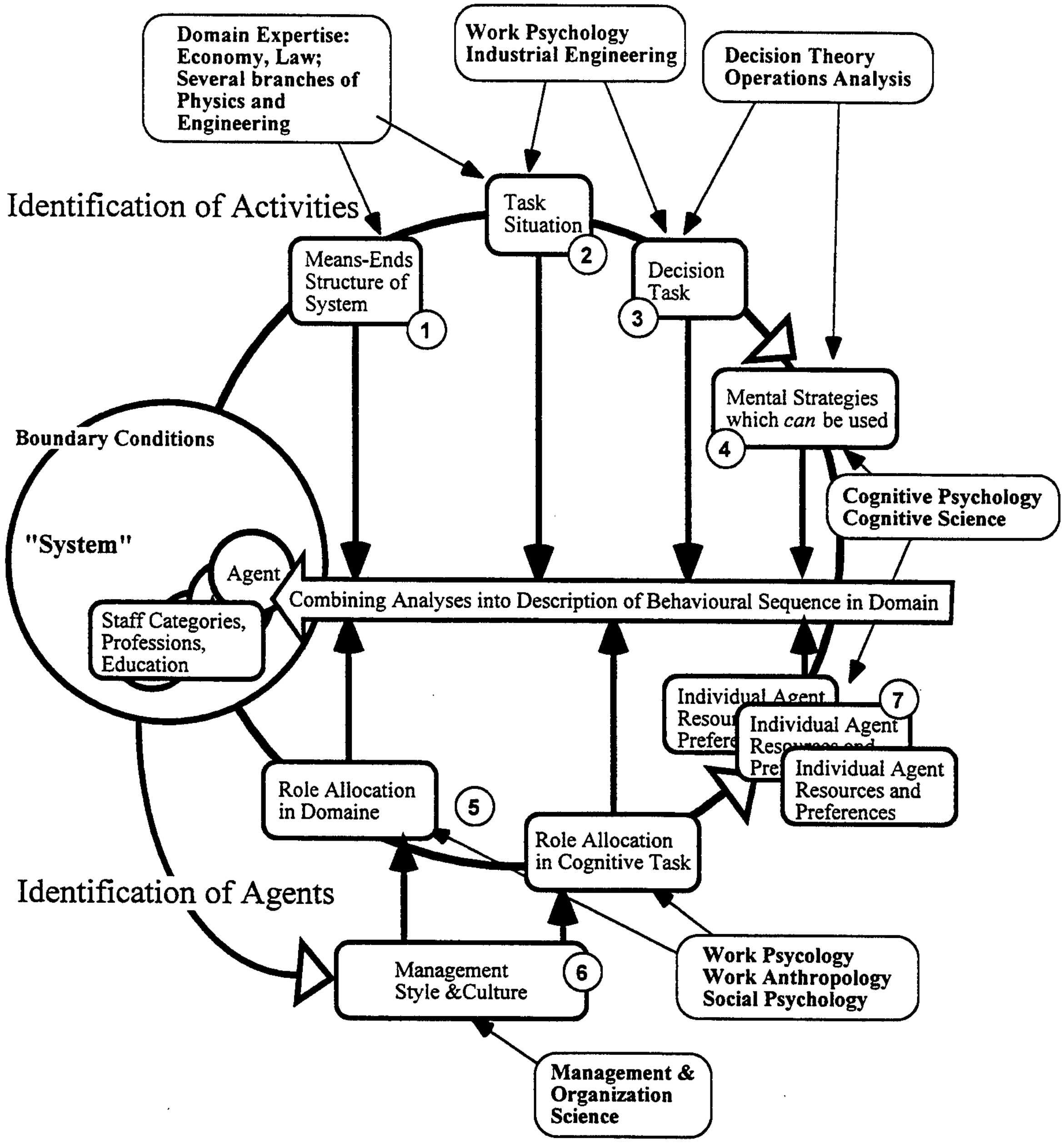

Figure 6.2 illustrates the perspectives of analysis of a taxonomy for cognitive work analysis. Two lines of analysis are used: The upper path of the figure shows the *identification of activities*. This is concerned with the 'work requirements,' which are to be compared to the agent's resources and preferences in order to determine the individual actor's preferences and likely choice of performance. The lower path shows the *identification of the agent*. This line of analysis is aimed at a description of the role, the resource profile, and the subjective preferences of the individual agents and an identification of the cooperative structure. Also the disciplines involved in the various analyses are indicated.

Facets of a Framework for Cognitive Work Analysis

1. **Work Domain, Task Space.** This facet of analysis :
   Goals and constraints of the work system; Value measures for priority judgments; General work functions in professional domain terms; Processes related to activities and tools; Topography, configuration, and material characteristics of resources such as land, buildings, people, and equipment.
2. **Activity Analysis in Domain Terms.** To be presented:
   All prototypical work situations and work functions relevant for information system design, labeled in domain terms.
3. **Activity Analysis in Decision Making Terms.** To be represented:
   The decision making processes of the work situations to be supported, such as: Information gathering; Situation analysis and diagnosis; Evaluation and priority judgment; Decision and choice; Planning; Execution; Monitoring.
4. **Information Processing Strategies.** To be represented:
   All strategies that <u>can</u> be used in the above information processes: Analytical, model-based strategies as well as empirical categorization-based strategies; and empirical heuristics and short-cuts.
5. **Allocation of Decision Roles.** To identify the actual user of a work station, the following aspects should be analyzed: 1) The structure and domain of work allocation. *What* is divided among staff members: work space, work functions or specialized work processes? 2) The criteria by which the staff members share work. *How* is it divided: By organizational tradition, union agreements, to work load, to have functional de- coupling, according to competency or information access?
6. **Management Structure and Social Organization.** The dynamic allocation of roles determines the *content* of the information to share; the *form* of the communication depends on the management style of the work system, that is, whether management is hierarchically authoritative or democratic and negotiating, etc.
7. **Mental Resources, Competency, and Preferences of the Individual Actor.** This facet serves to represent the cognitive resource profile, competency, level of expertise, and subjective preferences of the system users to identify the criteria for situational adoption of work roles and choice of strategies.

Figure 6.3. The dimensions of a work analysis to be used for information system design.

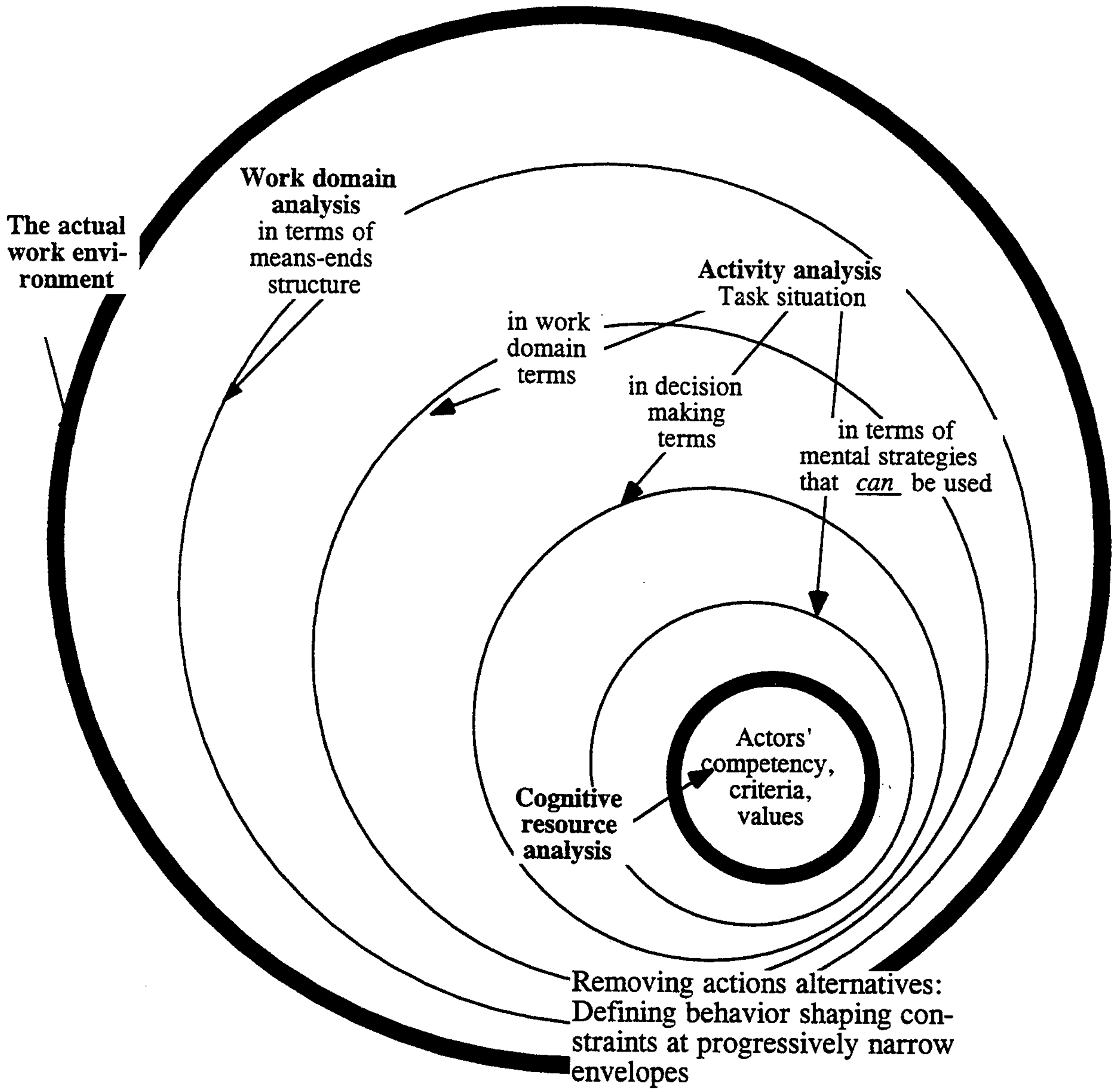

Figure 6.4. The shifts in language necessary to relate properties of a work environment to the cognitive resource profiles of the actors.

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7. WORK DOMAIN, SEAD TASK SPACE

The first level of analysis is the delimitation of the problem space to be the SEAD system embedded in the military systems-of-systems[16] and a representations of the ends, means, and constraints of this problem space, that is a representation of the behavior shaping deep structure of the system.

Analyses of the performance of experts in actual work in several different work domains have repeatedly demonstrated that the work space is perceived by actors as being a field of activity, spanned by two dimensions: One dimension is the *span of attention* shifting from consideration of the entire system to a focus on details. Another dimension is the *level of abstraction* used for description of the properties of the work space.

The space in which an actor mentally operates thus can be represented by a map spanned by the abstraction/decomposition axes. Such a map derived from a computer maintenance session is shown in figure 7.1 and illustrates some basic aspects of the modeling approach. Work behavior in a particular case can be represented by a trace across the map. During a problem solving tasks, an actor will tend to work his way down along the diagonal of the map, starting with an overall formulation of the objectives to meet, and ending with an explanation in terms of the process at the component level. The trace will be different in each particular case, demonstrating that actual work performance is represented better by the domain map together with the criteria guiding the actors navigation in the map than by a sequential task description. In the computer maintenance example, one actor takes care of the entire problem space. In more complex work settings, several actors will cooperate to control the state of affairs in the problem space. We will return to this issue below.

Control of a system involves operations on and through its internal constraints. In the computer case control can take place via the causal constraints of the physical part of a system or through the intentional constraints embedded in its program. These internal constraints are actually the sources of the regularity of system behavior that makes work planning ahead of action possible. To be useful for unanticipated problem situations, a representation of the problem space must define the functional inventory of the work system, that is, the functional territory within which the actors can navigate or, in ecological terms, the *affordance space*. In other words, it

[16] See e.g., Whitaker. R. D. and Kuperman, G. G. (1996): Cognitive Engineering for Information Dominance: A Human Factors Perspective; Tech. Report AL/CF-TR-1996-01 59.

identifies the world of 'possibilities' or, in Ashby's terms, the 'requisite variety' necessary to cope with all the situations which may appear during work. This feature makes the abstraction-decomposition map well suited for description of the SEAD problem space.

Independent work[17] by Flach, in cooperation with Armstrong Laboratory, supports this judgment.

The problem space representation of figure 7.1 can be generalized to be a representation in terms of a means-ends abstraction hierarchy, see figure 7.2. The means-ends representation is structured in several levels of abstraction.[18] At the lower levels, elements in the description represent the material properties of the system. When moving from one level of abstraction to the next higher level, the change in system properties represented is not merely a removal of detailed information about physical or material properties but information is added on higher-level principles governing the co-functioning of the various elements at the lower level. In man-made systems, these higher-level principles representing co-functions are derived from the purpose of the system, i.e., from the reasons and intentions behind the design. An important feature of this complex means-ends network is the many-to-many mapping found among the levels. If this was not the case, there would be no room or need for human decision or choice.

The higher levels of abstraction primarily represent properties connected to the purposes and intentions governing the work system, whereas the lower levels mainly represent the causal basis of its physical elements. Consequently, perturbations of the system in terms of changes in operating objectives will propagate downward through the levels, defining the *reasons* for the target states of operation. In contrast, the effect of changes of the material resources, such as introduction of new equipment or break down of major machinery will propagate up-wards, being *causes* of change of the actual states. Now, any operator striving to control the operating state of a system will have to operate on and through the internal constraints of the system. Control involves a change of the parameters of relational constraints in order to introduce a propagation of effects ultimately bringing the system into the intended goal or

[17]Flach, J.M., Eggleston, R., Kuperman, G. & Dominguez, C. (1998). SEAD and the UCAV: A preliminary cognitive systems analysis. Final Report. AFRL/HECI: Wright-Patterson AFB, OH..

[18]For a detailed discussion see Rasmussen, J. (1985): Role of Hierarchical Knowledge Representation in Decision Making and System Management. IEEE Transactions on Systems, Man and Cybernetics. Vol. SMC-15, No. 2, 1985, pp. 234-243.
Or: Rasmussen, J., Pejtersen, A. M. and Goodstein, L. P. (1994): *Cognitive Systems Engineering*. New York: Wiley.

target state. This control involves operation on the *causal constraints* of the physical part of a system, or on the *intentional constraints* originating in the other actors of the system or a control system. Whether one or the other mode of control is appropriate, depends on the task situation and the structure of the system.

7.1. Intentional versus Causal Constraints

The weight of the intentional constraints compared with the functional, causal constraints can be used to characterize the regularity of different problem spaces. The regularity of behavior of tightly coupled, technical systems has its origin in stable laws of nature and when focus is on control of technical equipment, such as an aircraft, the primary source of regularity of behavior can be traced back to the laws of nature. Thus, predicting this behavior in response to control actions can be inferred bottom-up from knowledge about the involved physical processes. This is e.g., the case when monitoring the response of UAVs to control actions.

In contrast, for representation of the higher, planning levels, intentional constraints guiding the behavior of cooperators and -in the SEAD context- opponents become very important. In planning support systems for cooperative work, we have the problem of making visible the intention behind the actions of cooperating actors. This is important for mutual understanding and resolution of ambiguities, often referred to as being the general problem of 'sense-making' in communication. It is well known from flight decks that replacement of common display and manipulation panels by dedicated computer terminals obscured operators' awareness of the activities and intentions of cooperating colleagues.

The significance of the intentional information for decision making in the SEAD context is clearly demonstrated by Klein's analysis of the "Harassing F-4," see appendix 7.1.

Another situation when communication of intent becomes very important is when operating systems with a high degree of automatic control such as UAVs under auto pilot control. In aviation, pilots' occasional difficulty in understanding the shifts of control modes by auto pilots is a well known and often discussed phenomenon.[19]

In modern technical systems, the objective functions - that is, the intentional structure or reasons for the desired functions - are often "hard-wired" into the

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[19] see Sarter, N. and Woods, D. (1992): Pilot Interaction With Cockpit Automation: Operational Experiences With the Flight Management System. International Journal of Aviation Psychology, 2(4), 303-321 .

system in the form of a complex automatic control and safety system. The control systems maintain plant state and operation in accordance with the high level, stable design goals - such as to fly according to a preplanned flight path and to do it as economically and safely as possible.

For system control, the contents of the information presented for system operators should reflect system functionality and reflect the causal constraints from physical laws as applied to the productive processes of the particular system including the limiting conditions set by the confinement. However, providing intentional information - the *reasons* for the design - is very important to improve system reliability. In order to understand the functions and the behavior of the automated control and safety system, the operators must be familiar with the *intended control strategies* underlying this system. This is because the internal functions of an automatic control system are only the medium for processing this intentional information and, consequently, has little significance except for the maintenance crew. Unfortunately, designers of decision support systems, in process control as well as aviation, pay only little attention to the communication of intentional information to operators, pilots, or support staff. The reason for this is that the rationale for design choices often has been embedded in professional and company practice and in industry standards. It is often very difficult to identify and make explicit the original reasons for a particular system design feature. Blueprints and functional explanations only communicate *what* and *how*, not important information about *why*.

When it later during operation is necessary to re-configure a system because of changes in requirements or major disturbances, the lack of intentional information often hinders understanding of system behavior and prevents effective intervention. This has been observed repeatedly in process control rooms as well as flight decks. In order to provide effective support, the analysis and deliberate consideration of the path of propagation of both functional and *intentional* information through the different organizations involved in design and operation are important issues.

7.2. Computers as Team Players

It has been frequently claimed that designers of computer automated functions should make the computers into "team players." This appears to be a somewhat narrow view. Actually, computers are mediators of a cooperation between system designers and system operators. Computers serve to represent the intentional constraints of operation that have been preplanned of a designer. This is also the role of instructions, operating procedures, course-of-actions and rules-of-engagements which serve to communicate intentional constraints of operation as planned by system designers and/or planners of system operation. The main difference being that computers themselves can/will activate the preplanned actions and active interference by operators is necessary to evaluate the stored intentions and up-date if necessary. In contrast, orders and instructions are implemented by system operators, and modifications to suit the local requirements are part of the normal game.

In any case, the system operators are completing the design to match a particular requirement *in continuous cooperation with designers and planners.* To do that effectively and reliably, they have to *understand the intentions* behind preplanned actions and their preconditions. As mentioned above, this is also the case for computer automation and it is not a question about computers as team players, but a much more general question of planning the cooperation among system designers, action planners, and system operators. This cooperation is mediated across space and through time by means of many different modes and means of cooperation. The fundamental problem is *how to communicate objectives, intentions, and preconditions* behind automated functions, orders, instructions, and advice in a way to make designers and planners into team even communication is constrained by such means.

The question of the level of professional competence of the team members to assume becomes a basic issue in creation of an effective system of cooperating 'designers,' able to adapt quickly to changing conditions. For professional actors, there is a level of detail below which instructions and course of action should not be given, the central issue is communication of intent and of *changes*, that is, information about new system properties outside present actor competence. The aim of ecological system design is to create a shared knowledge base representing the means and ends of the work system together with interface displays that serve to up-date and maintain actor competence.

Considering the centralized command-and-control nature of present military systems, this problem appears to be crucial for highly dynamic and situation depending missions such as SEAD operations based on centrally devised COAs (course-of-actions), when local commanders are supposed to improvise and act quickly.

7.3. The SEAD Problem Space

An abstraction-decomposition map for an SEAD system can be drawn in analogy to the computer map of figure 7.1, see figure 7.3.

This map should represent the 'requisite variety' from which the functions and resources relevant for a given mission situation can be instantiated. As was the case for the computer maintenance, the foot-print of a particular mission activity may largely be along the diagonal, but unlike the computer case, operation will shift through several different planning bodies and actors. See figure 7.4 and 5. This could be taken to imply, that information is only necessary to present along the diagonal, being high level information for general planners, and concrete low level information for equipment and weapon operators. However, given the need to improvise in a modern battle theater, information at all levels should be available also for part-function planners[20].

Considering the gaming nature of SEAD planning, two different problem spaces should probably be represented separately, one representing own resources, functions, and objectives and another one to capture the resources of the opponent together with hypothesis about the intentionality to derive from his operations, see figure 7.6.

Military operational organization is recently described as a system-of-systems,[21] a view matching well the attempts to fill-in the relevant functions at the various levels of part-problem spaces[22] are shown in figures 7.7-11. From the previous discussion it follows, that the upper levels are most relevant for the entire system, while the lower levels become particularly relevant for the detailed 'component systems.' It should, however, be carefully considered that even if missions are carefully planned, the local actors are supposed to be capable of effective improvisation. The "Vision" of the AFSAB explicitly realizes that

> "The war fighters will use the system in innovative ways not described in the manuals, and it is this experience that will define the path to success" (Op. Cit. p. 13).

To define the information windows to the problem space available for the individual actor, the means-ends space relevant for problem solving thus must be defined, see figure 7-11. The problem space of the individual decision maker or actor includes the part of the overall means-ends representation that is relevant for the local functions together with a means-ends representation of the local work tools (assessment and planning tools, simulators).

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[20] For a detailed discussion of significance of access to all the means-ends levels in problem solving, see Rasmussen, J. (1985): Role of Hierarchical Knowledge Representation in Decision Making and System Management. IEEE Transactions on Systems, Man and Cybernetics. Vol. SMC-15, No. 2, 1985, pp. 234-243.

[21] Whitaker. R. D. and Kuperman, G. G. (1996): Cognitive Engineering for Information Dominance: A Human Factors Perspective; Tech. Report AL/CF-TR-I 996-01 59.

[22] Source: Joint Pub 3-01.4 "JTTP for Joint Suppressions of Enemy Defenses (J-SEAD)" 25 July 1995, Joint Chiefs of Staff.

The problem space representation at the national level in which an SEAD is embedded is included in figure 7.7. This level is included, because it has been the definite experience from the Balkan engagement, that the actual decision making of the 'component commanders' of the international forces has been influenced and constrained very significantly by the public discussions and parliament decisions of the involved democratic countries. Watching the scenarios and related press conferences through the CNN broadcast during the Golf war also makes it very clear that the commanders, when planning missions, must carefully 'sell' the necessity of mission and the acceptability of risking the life of soldiers to the democratic bodies of their home countries. The influence of this upon objectives and decision criteria of the local decision makers must be well represented, together with the communication channels (Cf. the 'Book-Process' for the Joint Chief of Staff for approval and execution of a UAV reconnaissance mission in figure 5.2). The JTTP doctrines for SEAD explicitly states that such missions are not ends in themselves but should be an integral part of planning and execution of joint air operation. Thus, a representation of the problem space related to the level of a particular theater of operations will be important.

The actual control of the UAVs is represented in figure 7.11. Emphasis here is on the material resources and the active functions. Higher level goals and priorities are, by and large, communicated from above, but still reliable information is critical for situations when fast improvisation is necessary.

The means-ends space represent the requisite variety of functions in the system and must be stored in a *knowledge base* accessible by all actors within an organization (cf. The Marine Expeditionary Forces' requirements quoted in Section 2, p.4). The knowledge base should be a comprehensive inventory of available functions at all levels, the relevant functional targets and constraints, and the means-ends relations to choose from in decision making. The annotations of knowledge components for effective retrieval is a key design issue. Each functional element should be retrievable from queries in terms of *what* it is, *why* it should be used, and *how* it may be implemented, see figure 7.5 and 13. In addition, interfaces must be designed according to the level of abstraction and the span of attention (level of decomposition) relevant to a particular user. For a focused information search and for interface design, the formulation of behavior shaping constraints by a more analyses is necessary at dimensions of the framework, as described in the subsequent sections.

7.4. Problem Space of a Mission Scenario

For design of decision support systems, an instantiation of the global knowledge base is necessary with reference to a particular *task situation,* described in terms of the means-ends representation of the entire problem space. In the present context, further analysis is focused on the SEAD mission domain. Selecting the work situations to analyze involves an instantiation of a sub-set of the means-ends relations relevant for the functions to control in that situation.

The doctrines for SEAD missions distinguish three types of scenarios that should be considered key situations for support systems design:

- Area-Of-Responsibility/Joint-Operation-Area *(AOR/JOA) Suppression,*
- *Localized Suppression* and
- *Opportune Suppression*

These three classes of SEAD scenarios include different fields of attention with reference to the problem space in figure 7.3, and the related planning and execution functions will be adopted of actors at different levels of the military hierarchy, depending on the actual situation.

The problem space for AOR/JOA Suppression planning and coordination involves long term, wide preparedness and the space will be very similar to the general 'requisite variety' space for the SEAD system. For localized and opportune suppression, sub-sets of this space are relevant, and focus will be more directed toward the operational levels, shown in the mission and UAV spaces shown in figures 7.9 and 7.10. The listing of functional elements at the various levels of abstraction will neither be complete, nor accurate: they are only intended to be illustrative with respect to the different categories to be considered for discussion of the content and form of interfaces serving to couple the decision makers and actors to their problem spaces. A proper identification of the content of the problem space representation will ultimately depend on interviews with subject matter experts (that is, military strategists, mission planners, as well as system operators).

(AOR/JOA) Suppression at the mission theater is focused on suppression at a more general level to permit effective friendly air operations by protecting friendly airborne systems, disrupting enemy air defenses, and establish flexibility for friendly operations on both sides of the forward lines of own troops. A general description of the activities in domain related terms in the following section is derived from the JTTP doctrine.

7.4.1. Goals and Objectives

The JTTP formulation: 'To neutralize, destroy, or temporarily degrade enemy surface based air defenses by destructive and/or disruptive means.' To this objective implicitly existing objectives must be added, such as - and do it with minimal loss of lives and according to politically accepted codes and within constraints related to funds, resources and time limits.

From the press conferences relayed from the Gulf war, it is evident that an additional objective of a joint force commander is to plan missions to be immediately acceptable to democratic bodies and the general public.

7.4.2. Level of priority measures

This level represents the criteria and measures that are used to select functions and resources to comply with objectives and external constraints, that is, criteria to close the degrees of freedom found in the functional resources. Measures mentioned in JTTP are e.g., resulting increase in effectiveness of friendly air operations, degree of duplication of effort, level of system responsiveness. Again, additional general measures are implicit in the JTTP doctrine, such as minimize losses, probability of fracticide, likelihood of political intervention.

At the functional level, a measure of the degree of contribution from different available resources is mandatory for planning.

7.4.3. Level of general SEAD functions

SEAD missions require coordination of a very complex set of functions involving intelligence, planning, mission execution, and battle assessment:

Intelligence and data gathering is a complex function involving coordination of information sources, dissemination of data, and coordination of communication. At the (AOR/JOA) suppression level this includes National intelligence agencies, joint intelligence centers, as well as in-theater data collection assets. The function includes communication and computer architecture selection and control, de-conflicting of channels, and communication coordination with operations.

SEAD Planning involves integration of information from many sources about enemy ground force maneuvers, analysis of the location and strength of enemy systems, with emphasis on "main effort forces" that have the most effective protection (by SAM and AA systems). Evaluation of SEAD resources involves the analysis of the contribution from the distinct capabilities provided for SEAD functions by each component and the diverse combinations these capabilities will offer. The planning function involves several elementary functions which open different information windows to be considered for interface design:

- Review JFC objectives and concept of operations
- Collate and analyze SEAD target information
- Determine SEAD requirements and targets
- Assess impact of SEAD EW (Electronic Warfare) efforts
- Planning to avoid fracticide
- Coordinate joint EW support
- Assess threats along ingress and egress routes.
- Update SEAD order of battle
- Monitor mission results
- Recommend targeting guidance
- Develop C4-I protection measures
- Planning frequency and spectrum deconflicting

The resulting AOR/JOA plan will reflect JFC objectives, provide clear division of tasks among components, delineate coordinating instructions, and outline resources to be used. Furthermore, the plan integrates the SEAD execution processes to be used, such as destructive and disruptive measures to preclude mutual interference.

UAV mission planning is normally a function allocated the MCE - mission control element - or the UAV GCS - ground control station. The complexity of the planning stations vary with the UAV class and is greatest for the multiple endurance vehicle systems, such as e.g., the Predator and the Global Hawk.

Mission planning generates an integrated mission plan consisting of a navigation plan, communications plan, sensor plan, and dissemination plan. During the mission, the mission planning station can initiate dynamic mission updates as required to ensure conformance with emergent tasking and clearances. These mission updates can range from re-tasking the sensor for a single image through replanning the entire mission plan including flight track, sensor plan, and/or dissemination plan. From higher level tactical intelligence tasking and coordination information is received, including threat data, for the mission plan to ensure NRT threat awareness.

UAV mission execution involves several functions, such as vehicle control, payload control, data analyses, and information dissemination. Vehicle control includes several different elements such as launching and recovery, navigation with reference to the topography of the terrain; tracking targets in the terrain; avoiding threats from ground forces; and monitoring the state of vehicle onboard systems, fuel, etc.

In addition, functions as system maintenance and repair must be supported.

7.4.4. Physical SEAD Processes

For each of the SEAD functions, several different physical systems are available, and evaluation of their contributions during planning and control of their behavior during a mission require information about processes characteristics and limitations.

Intelligence and data gathering involves operation of a complex network of sensors, communication links and computers based on very different techniques, such as surveillance and weather satellites, AWACS and JSTAR aircraft, radar, reconnaissance UAVs, and computer networks.

Planning depends, in addition to the interaction with the intelligence system, on operation on data bases and retrieval networks regarding enemy and friendly resources, doctrines, COAs, plans, intentions, etc., together with facilities for simulation of mission scenarios.

SEAD mission execution countering enemy maneuvers involve the physical mission theater, its topography and the total inventory of enemy and friendly forces, their equipment for transport, support and action, in particular the enemy man-portable, transportable, or self-propelled tactical and strategic SAM and AAA systems and the friendly resources for SEAD operations. SEAD suppression measures are normally divided into destructive and disruptive means. *Destructive means* are aimed at the destruction of the target system or operating personnel. The effects are cumulative and increase aircraft survivability, but destructive means may place large demands on the available combat capabilities/forces. *Disruptive means* will temporarily deny, degrade, deceive, delay, or neutralize enemy air defense systems to increase aircraft survivability. Disruptive means may be either active or passive.

The means for destructive SEAD processes: aircraft delivering bombs, air and surface-to-surface missiles, air scatterable mines, and artillery and for disruptive, active means: electronic attack (anti-radiation missiles (ARM), directed energy, electromagnetic jamming and electromagnetic deception) expendables (chaff, flares, and decoys), tactics such as deception, avoidance, or evasive flight profiles, and unmanned aerial vehicles. Passive SEAD means include: emission control, camouflage, infrared shielding, warming receivers, and material design features.

According to the JTTP doctrine, operations may require support for suppression of enemy air defenses from resources outside the Airforce. This involves a significant extension of the means-ends space to consider during planning and coordination. Such support may include:

- Reconnaissance support to gain specific coverage in the area of operations.
- Electronic warfare (EW) to provide jamming of radar, data links, and voice communication signals.
- Capabilities/forces that provide jamming of enemy threat radars, and ground controlled interception (GCI) systems.
- Obscurants (smoke support) to degrade the ability of enemy air defenses to acquire targets.
- Attack helicopter and air attacks on designated enemy targets.
- Direct or indirect fire on enemy air defenses using weapons such as mortars, artillery, missiles, or naval surface fire.
- Direct action by special operations forces (SOE) to destroy air defenses or disrupt their activities.
- Synchronized ground or naval force maneuvers to disrupt enemy air defenses in an area of air operations.

The functional resources for SEAD mission execution thus present a very complex set of equipment and weapon processes, capabilities, and constraints, which planners will have to consider for a particular situation and which therefore should be well represented in a shared knowledge base.

UAV system control involves several different technical control tasks:

Launching and scheduling is based on the tasking order. The flight transit plan is prepared with reference to a topographic map, considering particularly well defended regions. The speed and altitude are entered the auto pilot, as well as wind direction and speed.

Vehicle control includes UAV flight control - direct or through auto pilot. Control is coordinated with air traffic control (ATC). During pre-planned flights changes to the UAV auto pilot are uplinked if deviations from flight plan are necessary. For some UAV systems, the vehicle control station provides for continuous NRT monitoring of several (usually up to three) air vehicles simultaneously, including air vehicle systems health and status, mission/threat status, and navigation, and allows the operator to dynamically control the air vehicle flight path and systems operation. The operator can modify the flight track through uplinking mission plan changes. Positive control of vehicle heading, altitude, or airspeed is provided to allow the operator to immediately respond to ATC/airspace coordination direction. The operator may also be able to control the aircraft threat warning and deception system and Identification Friend or Foe (IFF).

When the vehicle is automatic controlled, special automatic maneuvers can be inserted by flight controller, such as orbit, racetrack, figure-of-eight, or area searches. Choice of such modes depends on feedback from the image analysis function.

Direct remote control of the navigation of the vehicle or monitoring auto pilot performance while, at the same time, considering the needs of the payload operator, to be close to the targets, without being spotted will be done with reference to the topography of the theater.

Avoiding threats and tracking targets involve control of vehicle height, speed, yaw, etc. a control task which involves careful consideration of the constraints defined by the aerodynamic characteristics of the vehicle and the constraints defined by threat envelopes of enemy weapons. The task is tightly related to payload control, in particular during target tracking, see the discussion below.

Monitoring the state of vehicle systems during missions and ***maintenance*** of the onboard systems, fuel, power plant, hydraulics etc. depend on work processes and tools similar to those of industrial process systems.

Payload control and image analysis. Payloads are typically imaging systems such as high resolution video, infra-red, and radar imaging systems. Payload control involves the control of the elevation of azimuth and elevation independent of vehicle position and movement.

When this function is manually controlled, the function involves a multiple degree of freedom control task[23] (control of vehicle (altitude, horizontal position, yaw), and of sensors (pitch, yaw, and field of view)) and a control interface integrating the control laws of the vehicle and the payload should be considered. For this reason automatic modes may be present such as fixed elevation and azimuth of payload independent of vehicle, automatic control of azimuth and elevation for searching, fixing the pointing of the imager, or keeping track of moving target.

Dissemination of images and the results of detecting and recognizing targets can largely be automated when the imager is locked to a particular object. The analyst, however, has to mark the object by target type, sub-type and present activity for higher level planning units.

Physical processes of vehicle and support equipment. A representation of the relational structure and functional processes shaping the behavior of the air vehicles, their on-board technical systems as well as all support equipment also belong to this representational level.

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[23]Breda, L. van, (1995): An explanatory Study of the Human-Machine Interface for Controlling Maritime Unmanned Air Vehicles. In: AGARD Conference Proceedings 591: Subsystem Integration for Tactical Missiles (SITM) and Design and Operation of Unmanned Air Vehicles (DOUAV). Pp. 21.1-21.8.

7.4.5. Material SEAD Resources and Physical Configurations

This lowest level of the means-ends hierarchy represents the topography and topology of the mission space, together with an inventory of the material resources, their configuration, and their in the mission space.

Mission theater topography. At this level, the topography of the operations theater is represented at several levels of detail corresponding to the field of attention relevant for the different decision makers to support mission planning and execution. This representation includes location of enemy and friendly resources in terms of weapon and personnel categories. Terrain features, roads and other infra structures are to be represented including meteorological data etc. Important is a representation of enemy resources in terms of their operational characteristics, range of operation, numbers, visible profile, and locations are clearly important. For SEAD operations, equipment such as the following is in focus:

- SAM units: SA 2,3,6,7,8,9; HN5; Roland 2
- AAA units: 57, 85, 100, 130mm; ZSU-23-4
- Command, control, and communication centers and links.

Communication systems. For communications control station a representation of the equipment used to maintain the health and status of all communication sub-systems is important. The complexity of the communication systems is illustrated by the equipment available to the MCE (mission control element):

- Ground receive and transmit equipment is used to interface with UAVs and for theater communications.
- Air vehicle data links include a Ku Band terminal, Common Data Link (CDL) compatible LOS data link, and UHF SATCOM data links. All data links are secure and may have a voice channel for communications through a VHF/UHF voice relay primarily for airspace coordination. It serves communication with:
- Joint Surveillance Target Acquisition System (Joint STARS), Airborne Command and Control Center (ABCCC), Airborne Warning and Control Systems (AWACS), etc.
- MCE incorporates an ARC-210 for direct LOS VHF/UHF voice communications with airspace control authorities.
- The Ku Band Tactical Field Terminal (TFT) uses a 6.25m dish antenna to provide for satellite communications relay C2 uplink, and down links of health and status and wideband imagery. The TFT can uplink to the air vehicle at 200 kbps and receive down links at 1.5, 10, 20, 30, 40, or 50 Mbps.

- The Modular Interoperable Surface Terminal (MIST) uses a 2m X-Band antenna to provide LOS C2 uplink, and health and status and wideband imagery down links. The MIST uplinks at 200 kbps, and receives down links at selectable rates of 1.5, 10.7, 137, or 274 Mpbs.
- For beyond LOS operations, the MCE has a Demand Assigned Multiple Access (DAMA) SATCOM for Global Hawk C2/health and status. The DAMA SATCOM provides for operation of up to three air vehicles simultaneously on the same data link.

UAV - vehicles and support equipment. At the physical configuration level is included a representation of the physical characteristics of vehicles, the number of vehicles available for operations, their location, etc. The basic physical characteristics of typical vehicles are shown in Table 7.1.

The level also includes the inventory of support and transport equipment for the UAV groups.

7.5. Summary, Design of Interfaces

The functions and processes listed above belong to several different categories that have to be considered separately for design of interface systems:

- Situation assessment and mission planning related to military strategies and battle control;
- Control of large, tightly connected information systems supporting intelligence and information dissemination;
- Operation of work support systems, information retrieval in knowledge bases, operation of mission simulators;
- Planning 'from the outside' of trajectories to be followed by vehicles in a topographic space (ATC, UAV trajectories in battle space, etc.);
- Vehicle piloting 'from the inside' such as remote manual control of UAVs.
- Control, monitoring, and maintenance of technical equipment (such as on-board UAV systems and equipment).

This distinction will be discussed in more detail in sections 13-15.

"Harassing F-4s"[24]

In 1988, the Iran-Iraq war had endangered shipping in the Persian Gulf. An AEGIS cruiser was patrolling the Persian Gulf, to keep the sea lanes safe. On this particular day, the cruiser was escorting its unarmed flagship through the Gulf, in daytime. Two Iranian F-4s took off and, instead of patrolling the coast to the north or south began to circle the end of the runway. Each orbit brought the fighters closer to the U.S. Navy ships. The aircraft turned on their search radars, to scan for objects. Then the lead aircraft turned on his fire control radar used to obtain a radar lock-on to a target prior to firing a missile and acquired either the AEGIS cruiser or the flagship as a target. This was considered a hostile act and the commander would have been justified in firing a missile at the F-4s. However, his mission was to reduce hostilities, not increase them. He needed to defend his ship, and the flagship, but in his judgment the F4s were not going to attack.

He formed his judgment by trying to imagine that the F-4s were hostile. He could not imagine that a pilot preparing to attack would make himself so conspicuous. The pilots had been flying around in plain view. They further announced their presence by turning on their radars. They even used their radars unnecessarily, keeping them on when their circles carried them away from the cruiser. This was particularly unusual because the Iranians were having trouble performing maintenance on the radar systems, and tried to use them as little as possible. Yet here were aircraft making a big show of using their radars. The commander just didn't see how pilots intending to attack him would behave that way.

In contrast, he could imagine how the pilots were trying to harass him. All their actions seemed consistent with the harassment hypothesis, whereas the hostile intent hypothesis had some major flaws. Therefore, the commander inferred that the F-4s were just playing games.

He still needed to ensure self-defense, and he took the necessary actions–breaking the lock-ons from the F-4 radars, sending out radio warnings, and so forth. He also prepared his crew to look for telltale signs, such as swerving away, that might indicate that the F-4s had fired missiles. Finally, he determined the minimum range he could accept, and prepared to engage the F-4s if they got too close. Eventually the F-4s tired of the game, and flew off.

[24]Source: Gary Klein: Naturalistic Decision Making: Implications for Design. CSERIAC 93:01

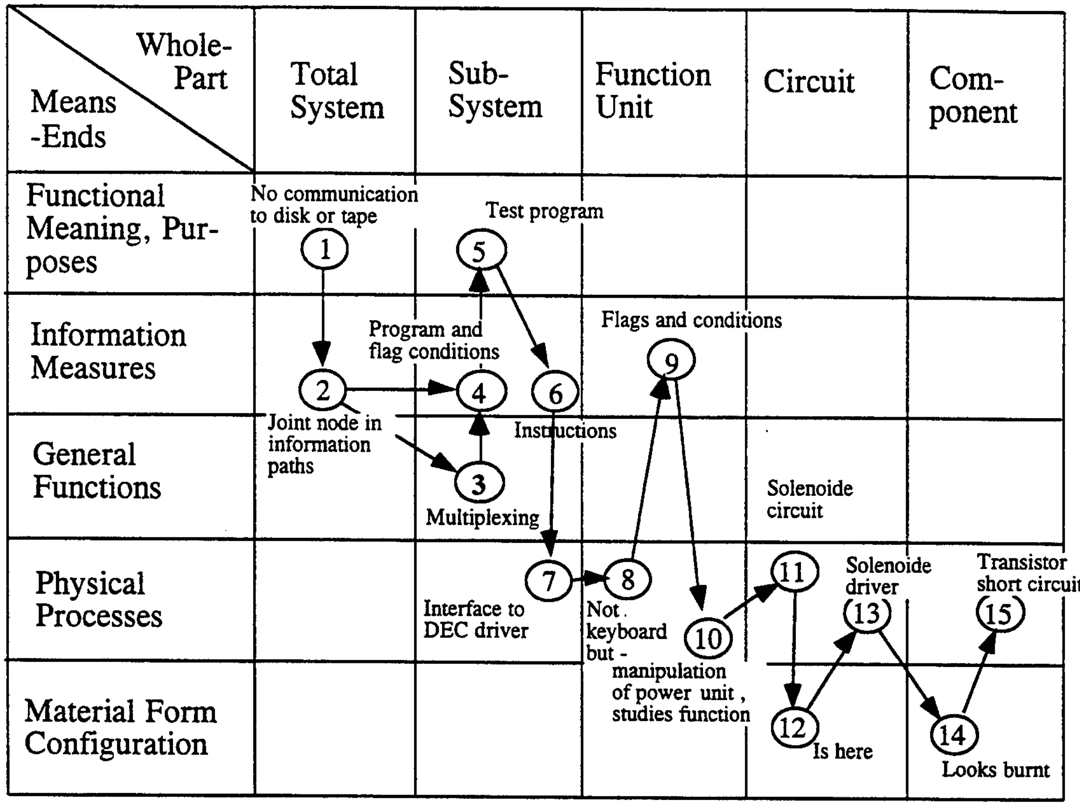

Figure 7.1. illustrates the varying span of attention of a maintenance technician's search for the location of a faulty component in a computer-based instrumentation system and the different levels of abstraction in representation he applies. His conception of the system is described by a map spanned by the means-ends and the whole-part dimensions. During the task, he largely moves through the diagonal of the map, he starts considering the general purpose f the whole system, goes though functions of sub-units and ends with the location of a physical component.

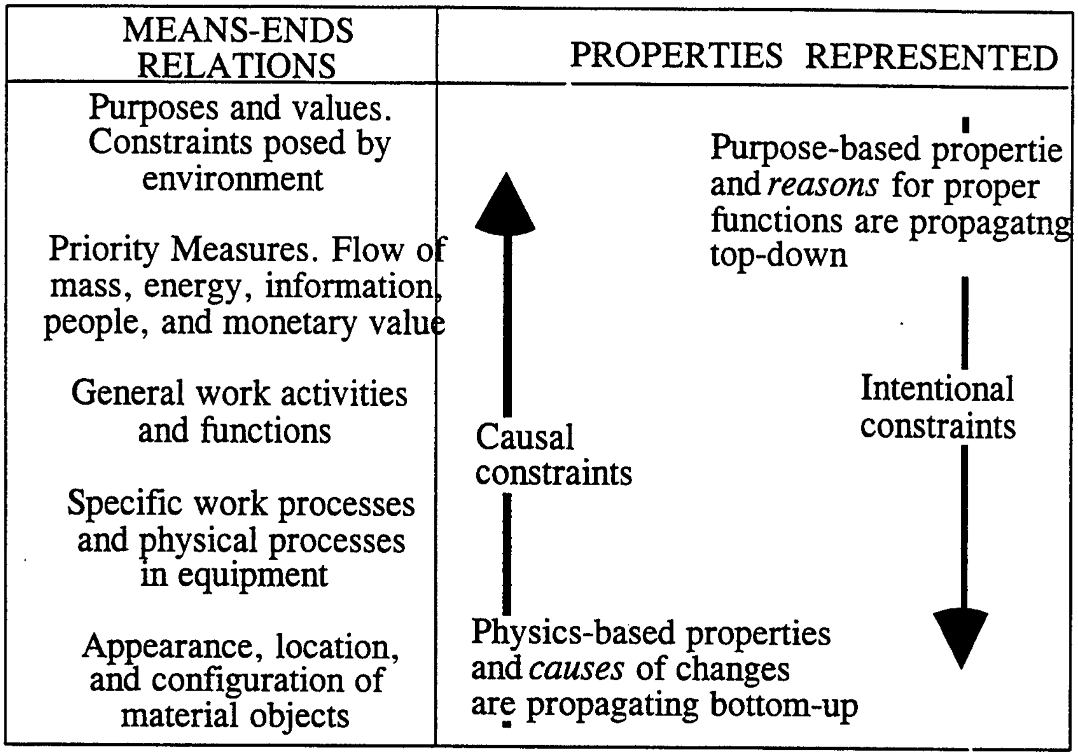

Figure 7.2. Any system can be described at several levels of functional abstraction adding up to a means-ends hierarchy. Lower levels are related to the physical configuration and processes. Higher levels to general functions and priority measures. Reasons for proper functions propagate top-down while causes of functional changes propagate bottom-up. The need and potential for human decision making depend on a many-to-many mapping among the levels of representation.

System-of-Systems	National Level	Theater of Engagement	Active Force, Air force	Mission SEAD	Component UAV System
Goals & purposes					
Priority measures					
General functions					
Physical processes					
Inventory Configuration Topography					

Figure 7.3. The total problem space of a military mission, such as e.g., a SEAD mission can be mapped by a means-ends/whole-part representation similar to figure 7.1. The map above is subsequently used to represent the allocation of space to decision makers, see figure 7.4.

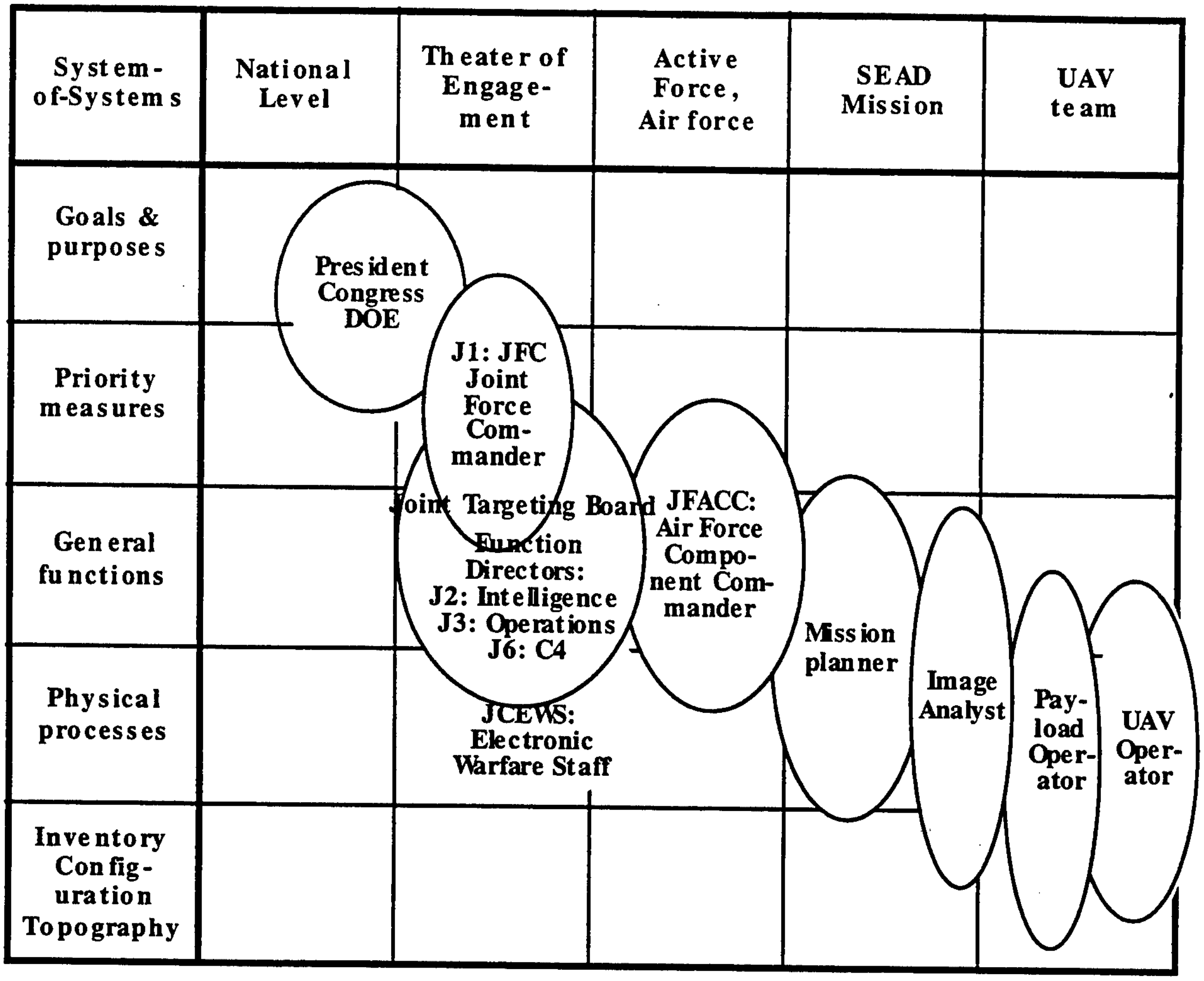

Figure 7.4. The figure shoves the problem space of SEAD – suppression of enemy air defense. The map is spanned by the abstraction and decomposition dimensions, and the foci of attention of the various organizational units and actors are indicated. The tendency during routine operations to focus along the diagonal is indicated.

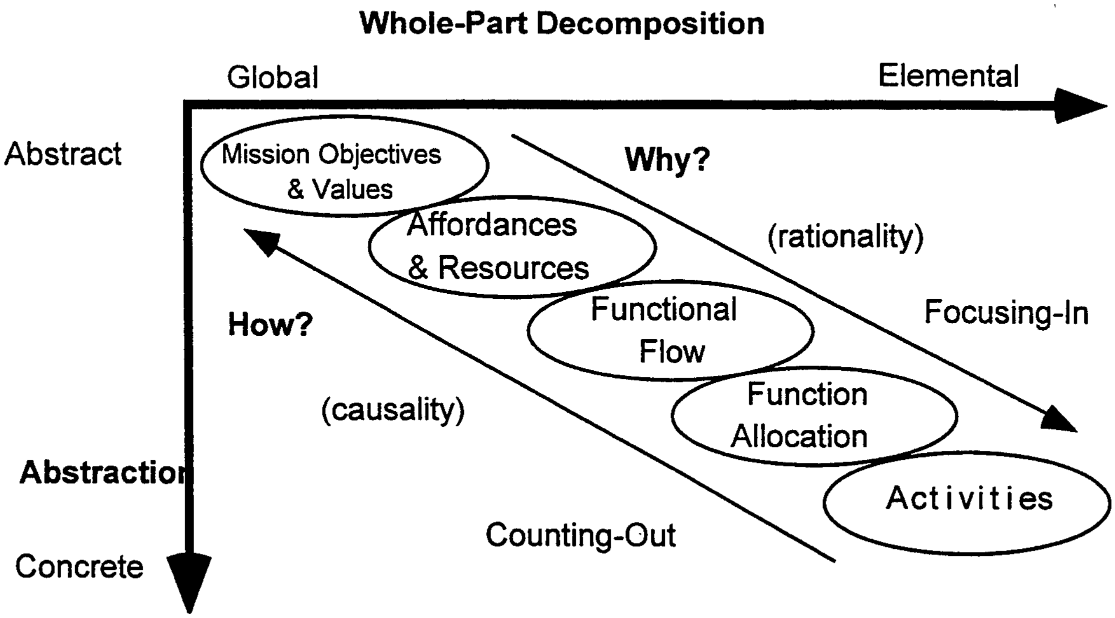

Figure 7.5. An independent analysis[25] illustrates this tendency of activities to be concentrated along the diagonal and to change in content. "Reasoning down the diagonal helps to reveal the rationality that determines why things are done. Reasoning up the diagonal helps to reveal the causal relations that determine how things are done." Compare to figure 7.12.

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25 Reproduced from Flach, F., Eggleston, R., Kuperman, G. and Dominguez, C. (1998): SEAD and the UCAV: A Preliminary Cognitive Systems Analysis; Dayton, Oh. Wright Patterson AF.

Enemy Systems	Space of Targets and Threats
Enemy Goals & purposes	Defend against intruding air forces, within resources Protect own resources and staff
Priority measures	Enemy perception of success vs. being hit *(During desert storm, Wild Weasels beat up on the enemy so badly that they essentially stopped radiating. Severely hampered by the coalition's effective SEAD operations, they would come up for four or five seconds at a time, shoot and go back down again, leaving the missile unguided and ballistic. In fact, the Weasels were so effective that when the Iraqis passively detected the F-4Gs distinctive APQ-120 radar, they often would not even bring up their SAM radars).*
General EAD functions	Attack intruding forces, defend own resources by choosing the appropriate weapon and most effective ROE - rules of engagement *(Reverse engineering of enemy rules of engagement and air defense order of battle can serve to identify criteria of choice and priority measures);*
Physical processes of EAD resources	Physical, functional characteristics of threat sources, SAM & AAA: - Range of threat, speed & maneuverability (G & curve radius) of missile - Radiation characteristics, radar, IR, frequency, transmission patterns - Mobility and transport characteristics of unit - Vulnerability characteristics, thickness of armor, Physical, functional characteristics of C3 links: - Frequency, transmission patterns, - Vulnerability characteristics,
Inventory Configuration Topography	Map of theater territory with location and type of thread sources Thread sources: Configuration, size, visible profile: - SAM units: SA 2,3,6,7,8,9; HN5; Roland 2 - AAA units: 57, 85, 100, 130mm; ZSU-23-4 - Command, control, and communication centers and links

Figure 7.6. The figure shows the space of enemy operations in means-ends terms. A peculiar aspects of military operations is the 'gaming' nature of the task. Goals, intentions and performance criteria are shaped by analysis of the intentions, criteria and resources of the enemy, and reconnaissance UAVs have the main objective to collect information about the enemy space and the influence of battle (battle assessment).

System-of-Systems	National Level
Goals & purposes	Peace, Human rights, trade, Objectives of national policy and international treaties
Priority measures	Trade deficit, level of thread to citizens, public opinion
General functions	UN-intervention, diplomacy, trade-boycott, military intervention
Physical processes	
Inventory Configuration Topography	

Figure 7.7. Illustrates schematically the national context in which a SEAD mission is to be planned.

System-of-Systems	Theater of Engagement
Goals & purposes	Balkan peace keeping within stated policy and allocated resources, considering international relations and public opinion.
Priority measures	Number of refugees and lost lives, threat to US citizens, public opinion, votes in Congress
General functions	Humanitarian help: Transportation of personnel, food, medicine, etc. Diplomacy, Military intervention: Protection of humanitarian services, monitoring activities of military and para-military activities, intervention in conflicts, intelligence
Physical processes	
Inventory Configuration Topography	

Figure 7.8. Schematic sketch pad to be used for more detailed analysis of means and ends at the Theater of Engagement such as e.g., at present in Balkan. For planning at the theater of engagement, reliable, fast up-date information at the higher levels of goals and priorities have proven vital for forces representing democratic nations with an active public opinion and parliaments involved in day-to-day decisions.

System-of-Systems	Force Components: Air Force
Goals & purposes	Mission objectives within allocated resources for military engagement or humanitarian missions, respecting international conventions, while protecting military personnel and civil population, and considering political and public opinion;
Priority measures	Cost-effectiveness of missions: probability of success/loss/fratricide. (The enemy air defense order of battle, its system capabilities, and the flight profiles and defensive capabilities of projected friendly aircraft is used by the JFACC to develop a recommended threat priority list).
General functions	Organize commands and forces and employ those forces as necessary to accomplish assigned missions; develop objectives and guidance for the joint operation or campaign and specify the roles of air, land, maritime, space, and special operations forces in the conduct of the joint operation or campaign; establish requirements for SEAD to facilitate these operations; Surveillance, monitoring, intelligence (AWACS, JSTARS, UAV) Transport, supply, Combat (SEAD, etc.),
Physical processes	Resources as specified at the lower decomposition levels;
Inventory Configuration Topography	

Figure 7.9 shows a map representing the problem space of one of the forces active in the theater of engagement.

□

System-of-Systems	SEAD Mission
Goals & purposes	Mission objectives within allocated resources: "immediate objective is to permit effective friendly air operations by protecting friendly airborne systems, disrupting cohesion of enemy air defenses, while respecting international conventions and protect Air force personnel and civil population;
Priority measures	Planning criteria: priority of combat vs. SEAD. Cost-effectiveness of mission: probability of success/loss/fratricide. (The enemy air defense order of battle, its system capabilities, and the flight profiles and defensive capabilities of projected friendly aircraft is used by the JFACC to develop a recommended threat priority list).
General functions	Planning: conduct SEAD planning as directed by the JFC; develop intelligence requirements; support component commanders in developing planning priorities; allocate assets to conduct SEAD operations; request SEAD support from the JFC or other component commander; direct and control operations, monitor SEAD activities, Active operations: attack, destruction, disruption; Threat detection and identification; Coordination with surface support: (e.g., field artillery, naval surface fire, surface-to-surface missiles);
Physical processes	Functional characteristics of vehicles, F15, F16, F4-G, UCAV, URAV: - Speed & maneuverability (potential for evasive flight profiles, G limits & turning radii); - Vulnerability characteristics, thickness of armor, radiation characteristics, radar, IR, Functional characteristics of weapons: - destructive (Bombs, missiles, mines, artillery) and - disruptive (electromagnetic jamming and electromagnetic deception, expendables (chaff, flares, and decoys) ; Functional characteristics of sensors: - Intelligence Collection (AN/APG-70, Lantirn, Pave Tack, PDF (ELINT) - Threat detection and identification(AN/APG-70, Lantirn, ESM).
Inventory Configuration Topography	Map of theater territory with location and type of Vehicle types, equipment, types and numbers Weapon types: Sensor types:

Figure 7.10. The instantiation of the problem space during a mission, such as SEAD. This figure is at a level of decomposition where the representation of the material resources become critical.

System-of-Systems	Component System: UAV
Goals & purposes	Objectives: support of operations according to mission plans.
Priority measures	Cost-effectiveness of mission: probability of success/loss; Threat priority list from JFACC;
General functions	Planning: collect and distribute intelligence on enemy air defenses, nominate SEAD targets,; monitor SEAD mission results; forward mission results to the JFC and other component commanders; Mission planning and control, control of UAV flights; Collection and distribution of battlefield intelligence and battle damage information; Air strike and combat guidance, area searches, route reconnaissance, target location;
Physical processes	Ground control station: - Observer bay: information collection, analysis, and communication; - Tracking bay: monitoring UAV position; - Remote receiving station: real-time, remote reception & distribution of TV images and intelligence data; - Pilot bay: navigation processes, GPS; flight control; Vehicle characteristics: - Speed, maneuverability, flight profiles, etc. Payload characteristics: high resolution TV & FLIR, radio relays, meteorological sensor, radiac sensor, chemical detection, and COMINT;
Inventory Configuration Topography	Map of theater territory with location and type of resources, communication centers, ground stations, portable stations, tracking units, remote receiving stations; Number and configuration of UAVs (Predator, Global Hawk, Darkstar, Pioneer, Hunter, Outrider, Gnat 750, Tiltrotor UAVs), their equipment, weapons, sensors.

Figure 7.11. The means-ends space at the detailed UAV system level.

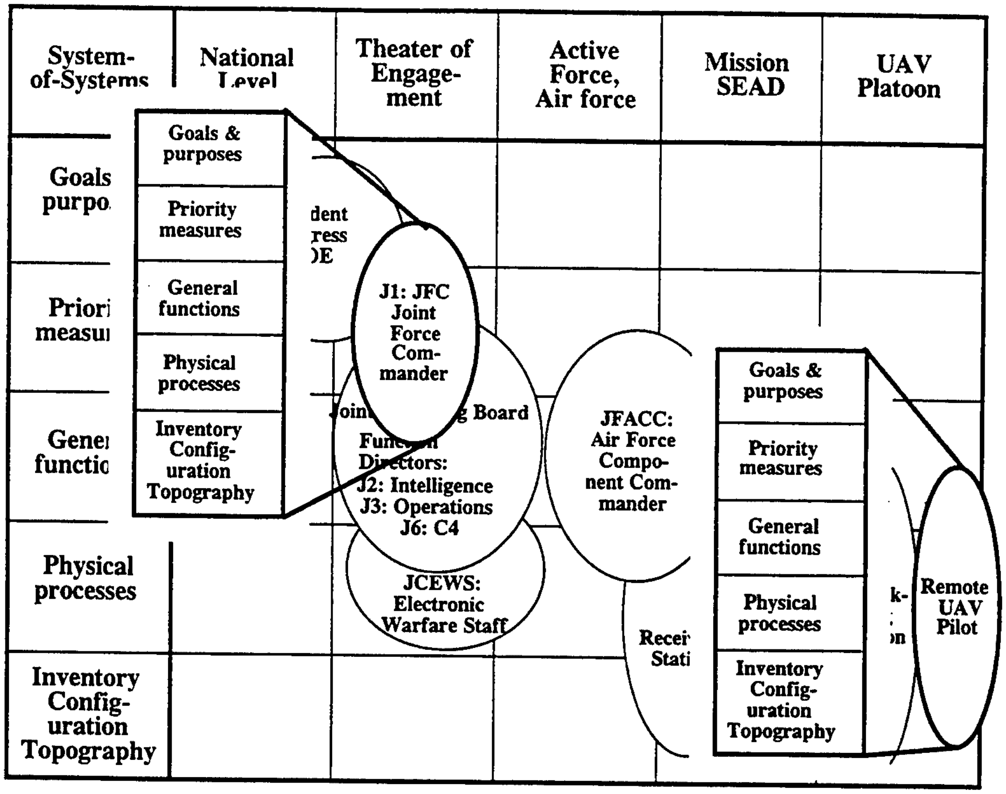

Figure 7.12. The means-ends space figure 7.3 shows the means-ends possibilities of the entire system of systems with respect to the system subject matter contents. When attention is directed toward the coupling of the individual decision makers to their particular work space, they are not only working on the subject matter space of the system, but also on their local work environment.

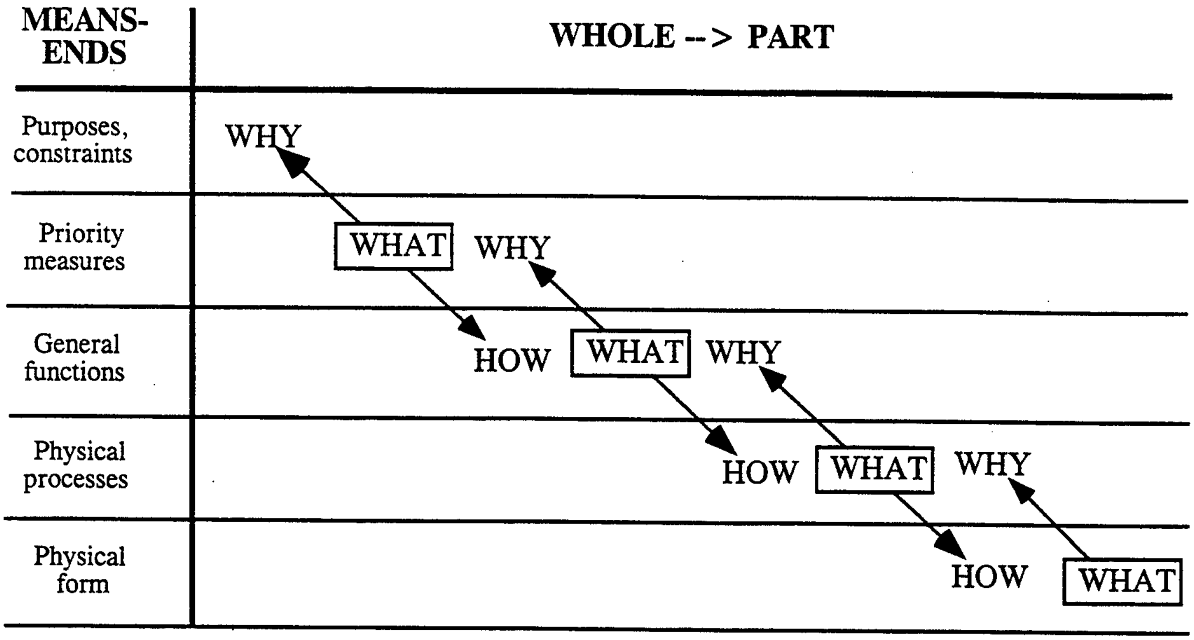

Figure 7.13. The Why, What, How relations of the elements of a knowledge base.

Characteristic	Predator	Global Hawk	Dark Star
Gross Take-off Weight	>1873 lbs (EO/IR)	22,914 lbs	8,600 lbs
Wingspan	48.7 feet	116.2 feet	69 feet
Mission Duration Operating Radius	24+ hours on station @ 500 NM	24 hours on station @3000 NM	> 8 hours on station @ 500 NM
Maximum Endurance	40+ hours	42+ hours	N/A
Ferry Range	N/A	15,000 NM	N/A
Payload	>450 lbs	2,000 lbs	1,000 lbs
True Air Speed	60-110 knots	350 knots	>250 knots
Loiter altitude	25,000 feet max. 15,000 Feet Nominal	>50,000 feet	>45,000 feet
Survivability Measures	None	Threat warning and ECM	Very low observable
Command and Control	UHF MILSAT/Ku Band SATCOM/C-band LOS	UHF MILSAT/LOS	UHF MILSAT/LOS
Sensors	SAR: 1 ft IPR, Swath Width Approx. 800 m EO: NIIRS 7 IR: NIIRS 5 Simultaneous Dual Carriage	SAR: 1 m search; 0.3 m spot EO: NIIRS 6 IR: NIIRS 5 Simultaneous Dual Carriage	SAR: 1 m search 0.3 m spot EO: NIIRS 6 IR: None Single Carriage
Coverage per mission	13,000 sq NM search imagery	40,000 sq. NM. search imagery, or 1,900 spot image frames	14,000 sq. NM search imagery, or 620 spot image frames
Sensor data transmission	Ku Band: 1.5 Mb/sec UHF SATCOM 16Kb/sec LOS: C-band 4.5Mb/sec	Wide band COMSAT: 20-50 Mbits/sec LOS: X-Band Wide Band (CDL): 137-275 Mbits/sec	Narrow band COMSAT: 1.5 Mbits/sec LOS: X-Band Wide band (CDLS): 137-275 Mbits/sec
Deployment	6 C-141s or 10 C-130s 2/C-5/C-17	Self deployable, SE requires airlift	3 C-141s or Multiple C-130s
Ground Control Station	LOS & OTH	Maximum use of GOTS/COTS (LOS & OTH)	Common with Tier II Plus
Data Exploitation	Existing and Programmed: JSIPS, CARS, MIGS, MIES, JIC, NPIC	Existing and Programmed: JSIPS, CARS, MIGS, MIES, JIC, NPIC	Existing and Programmed: JSIPS, CARS, MIGS, MIES, JIC, NPIC

Table 7.1. The characteristics of UAV classes.

8. ACTIVITY ANALYSIS IN DOMAIN TERMS

The functional inventory of the work space in terms of the means-ends hierarchy can, to a large degree, be mapped from studies of policy statements, organizational descriptions, doctrines, annual reports, operational procedures, and technical manuals. This map represents the multitude of functions to be controlled by the personnel, and the reasons for doing so. To come to a proper analysis of the activity unfolding in the control of this work space, the actual work practice must be studied on more detail through interaction with the various actors involved in specific, 'prototypical' task situations. The analysis should identify the means and ends which the individual actor will face in a particular work function, not only in terms of the basic problem space, but also including the local work support tools and equipment, see figure 7.12.

This activity analysis in work domain terms is actually an instantiation of the work functions listed in the means-ends hierarchy in a particular situation, an identification of the degrees of freedom for choice of means open to the actor, and of the local and subjective performance criteria applied to close the degrees of freedom. In this way, the analysis is not a classic task analysis, but an identification of options and constraints when serving a particular work function. Representation of activity in a work situation will supply a network of 'prototypical' task situations, frequently served by different actors, together with an identification of the content and form of information exchange among these situations.

The structure of the representation will be similar to the map shown in figure 8.2 for the UAV-BPI planning situation, supplemented with a map indicating the locations of the relevant information sources within the means-ends map.

Identification of the communication links and content of shared information is an important part of the activity analysis. A format as the one shown in Table 8.2 is useful for this purpose and will facilitate the generation of the communication matrix shown in figure 11.2 and the related identification of the functional organization, which will be active for a particular mission situation. A communication analysis for a set of representative task and mission scenarios will be necessary, for examples of task situations, see figure 8.3.

The kind of information required for an activity analysis as it is described here can be illustrated by the 'UAV divert scenario' found in appendix 8. 1. which also demonstrate the cooperative system directly involved in the execution of a UAV mission. This scenario demonstrates very well how the information of relevance to a user during the propagation of data upward through the system is integrated to higher aggregation levels and re-interpreted at increasingly general levels of abstraction.

APPENDIX 8.1: THE DIVERT[26]

The unmanned aerial vehicle (UAV), nearing completion of a pre-planned, optical intelligence mission (in general support of the MAGTF), is traveling along a designated flight path from its terminal loiter area, and nearing the portable control station (PCS) hand-over-control point. While not specified as a surveillance mission, the UAV's flight path overflies terrain which is unfamiliar to ground control station (GCS) personnel. As such, and in order to optimize their battlespace awareness, the UAV mission commander advises both the internal pilot and the payload operator--a captain/9910 and sergeant/0861 respectively--to monitor the real-time (RT) video imaging product provided by the UAV's day sensor device (a TV camera) and the GCS systems. Downlink telemetry reveals an open terrain composite, generally flat, with little elevation relief and sparse vegetation. Unexpectedly, the GCS video monitor displays the unmistakable dust signature of what appears to be a formation of armored vehicles moving at a high rate of speed. Upon detection, the UAV payload operator immediately signals the UAV via the primary up-link control (C-band) radio link, and changes the day sensor field of view profile from wide band to narrow band. Concurrently, the payload operator--a seasoned scout observer, NCO--also activates the day sensor's zoom lens. While this unexpected ground vehicle movement is occurring just slightly abeam the UAV's flight path, the immediate actions of the payload operator fails to achieve anything more that a tentative identification. Nonetheless, relying on an extensive forward observer background, the payload operator knows the UAV has detected a choice target of opportunity and thus advises both the UAV internal pilot and mission commander.

Recognizing that these suspected armored vehicles represent much more than a simple target of opportunity, but rather, a very real threat to ground units operating just a few kilometers away, the UAV mission commander inquires into the air vehicle's fuel status and, with acknowledgment that sufficient fuel is onboard, orders the internal pilot to immediately modify the UAV's flight path to allow continued surveillance of these suspected armored vehicles.

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[26]Source: Reconnaissance, Surveillance, and Target Acquisition Collection Planning--Embedded Within the MEF Intelligence and Operations Cycles. Authors: Intelligence Doctrine Working Group; May 1995; Chairman: Major J.C. Dereschuk, United States Marine Corps (www.clark.net/fas/irp/eprint/derescheck.htm).

In order to gain a positive target identification, the UAV mission commander recognizes the need to loiter the UAV and that in doing so, the UAV will deviate from its pre-planned loiter areas/surveillance routes. Thus, the mission commander initially coordinates the UAV's revised positioning and altitude with both the Ground Combat Element (GCE) Direct Air Support Center (DASC) and GCE Fire Support Coordination Center (FSCC) and then advises the MEF SARC of the UAV's discovery.

The SARC watch officer acknowledges the message and advises the UAV mission commander to continue as if an immediate tasking had been received. The SARC watch officer conducts the requisite advisory with G-3/G-2 agencies, and using one of the two remote receiving stations (RRS), monitors the identical real-time, video imaging product available to the GCS. The UAV's reprogrammed flight plan is no sooner coordinated with all concerned agencies and up-linked to the air vehicle when its first fly-by confirms what the payload operator suspected--this is a formation of four enemy armored vehicles traveling at high speed.

With positive identification established, the UAV mission commander, located at the GCS, provides the target description, location, direction of travel and estimated rate of march to both the MEF SARC and GCE FSCC. Additionally, based on the advice of the internal pilot, the UAV mission commander informs the SARC that the UAV has constrained loiter time, due to limited fuel, and recommends transfer of target observation responsibility to a manned, airborne platform.

The SARC watch officer informs the UAV mission commander that all concerned want the target immediately engaged and directs that the GCE DASC/FSCC be contacted in order to coordinate observation and attack responsibility. Surface observation is not possible due to the extended range, just as attack via surface means, i.e., artillery/ naval surface fires, is impossible for the same reason. This fleeting target, not yet in range of surface fires, requires an immediate air attack, or a target rich environment will be lost.

DASC and Tactical Air Operations Center (TAOC) coordination of two F/A-18s returning from a combat air patrol (CAP) mission is accomplished, and these aircraft are sortied-in to attack this target of opportunity. However, the inbound aircraft must traverse 150 kilometers, then acquire the fast moving vehicles prior to attacking.

Fortunately, a Tactical Air Coordinator (Airborne) (TAC(A)) aircraft is operating nearby and is diverted from its primary mission of coordinating close support to assist the attacking F/A-18s. While not a forward air controller (airborne) (FAC(A)), the TAC(A) is capable of acquiring the target and orienting the two F/A-18s.

Having confirmation that the TAC(A) has acquired the moving armored vehicles, the DASC informs the UAV mission commander that observation pass-off is completed. So ends the UAV's role in the acquisition and surveillance of this target. The two F/A-18s roll-in on the enemy formation, deliver their ordnance and the TAC(A) reports four armored vehicles destroyed.

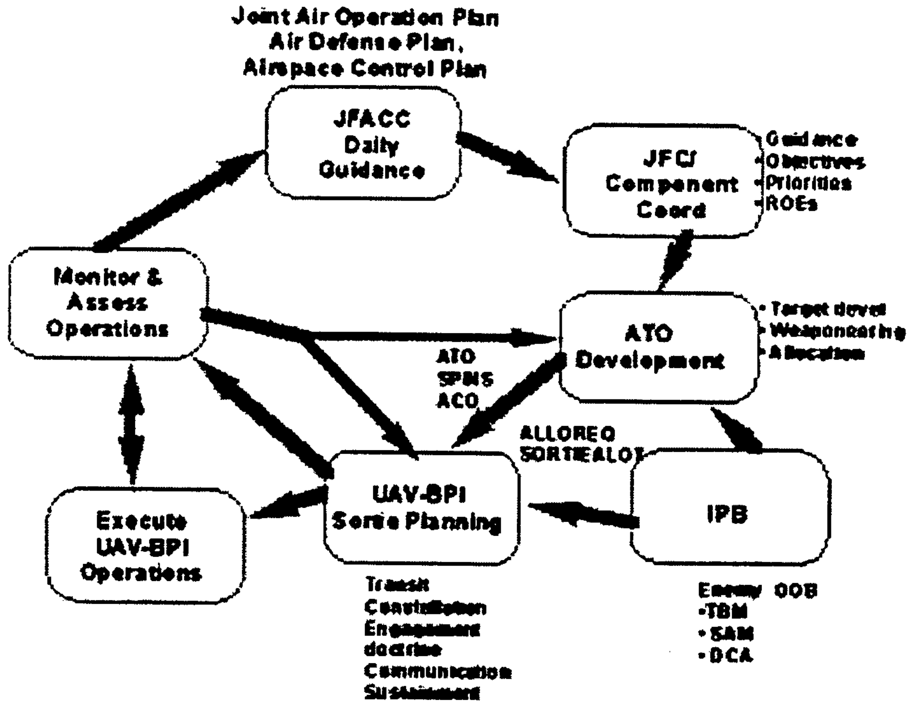

Figure 8.1. The figure shows a map of 'prototypical' work situations involved in BPI-UAV system operation[27].

Information Sources			Communication Links		Information Receivers		
Work situation	**Function, task**	**Who is the sender**	**Message content**	**Message form**	**Work situation**	**Function, task**	**Who is the user?**
Reference to map of prototyp-ical work situations.	Reference to function in means-ends map	Identify actor	Subject matter	Voice, image, report, letter,	Reference to map of prototyp-ical work situations.	Reference to function in means-ends map	Identify actor

Figure 8.2. A useful format for listing the communication links among the prototypical work situations as mapped in figure 8.1. The list is used for the generation of a communication matrix (figure 11.2) during the analysis of the functional organization in section 11.

[27]Source: Section 4.0: BPI System Operation. WWW download: http//208.202.180.2/UAV-BPI/Conopsdoc/Sec4.htm. Report title and other sections were not accessible.

Agent	Function
JFC: Joint Force Commander	- Organize commands and forces; - Develop objectives; - Guide joint operation and campaign; - Specify role of air, land, maritime, space and special forces.
JFC Staff	
J-2: Joint Force Director for Intelligence	- Anticipate and control All-source intelligence collection and analysis efforts. - Coordinate with J-3: Director of operations - Coordinate with component commanders,
J-3: Joint Force Director for Operations	- Assists JFC in directing and controlling operations - May be tasked to coordinate SEAD
J-6: Joint Force Director for Command, Control, Communications and Computers	- Plan communications - computer support - System architecture and deconflicting - coordinates with J-2 and J-3
JCEWS: Joint Force Commander's Electronic warfare Staff	- Provides EW expertise, - plan and coordinate joint activities including SEAD - includes personnel from each component of joint force, - headed by J-3 electronic warfare officer - includes a J-2 representative
JTCB: Joint Targeting Coordination Board	- Role defined by JFC - coordinate targeting information - develop targeting guidance and priorities - operates at the macro-level supporting JFC broad targeting guidance, not interfering with component commanders
JFACC: Joint Force Air Component Commander	- Responsible for planning and coordination of AOR/JOA SEAD
Component Commanders:	- Determine and plan SEAD support of their missions (Figure II-2): - Develop intelligence requirements - Collect and distribute intelligence on enemy air defense - Nominate SEAD targets - Allocate assets for SEAD - Request support from other component commanders - Monitor mission results - Forward mission results to JFC and other components.

Figure 8.3. A list of actors and prototypical decision situations relevant for analysis of the work situation: (AOR/JOA) SEAD planning.[28]

[28]Source: JTTP for Joint Suppression of Enemy Defenses. (J-SEAD). Joint Pub 3-01.4. USAF Joint Staff: July 1995.

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9. Activity Analysis in Decision Making Terms

The next level of analysis is focused on the decision making tasks involved in the task situation discussed above. The analysis involves a transformation of task functions into a representation phrased in information processing terms, such as situation analysis, goal evaluation, planning and action. This analysis should make it possible to relate task requirements to cognitive processes and resources. To do this, the different decision processes applied by decision makers depending upon their level of expertise and on the familiarity of the situation must be captured by the analysis.

For this purpose a framework is used (the 'decision ladder' in figure 9.1) which is closely related to Klein's 'cognitive task analysis' and the 'OODA model.'[29]

Analytical decision making involving situation analysis, goal evaluation, decision and planning follows the knowledge-based legs of the ladder. In familiar situations, however, short-cuts are used, based on familiar cues and stored plans, or pure recognition and expert skills. The ladder supplies a map of the various information processes that can be used to connect the different states of knowledge, that require very different processing resources, and that may be are used by different individuals involved in cooperative planning.

One important purpose served by the diagram is to define prototypical 'states of knowledge' serving as 'stopping points' in the flow of a decision process. They connect basically different information processes (deduction, induction, evaluation, etc.,) and define points suited to interact with other cooperating decision makers (and computers). Thus they define knowledge states to be considered for design of computer and communication interfaces. A preliminary attempt to illustrate how the decision ladder can be used to define the role of various decision makers in a collaborative planning task is shown in figure 9.2 (based on the command and control discussion in JTTP).

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[29]Whitaker. R. D. and Kuperman, G. G. (1996): Cognitive Engineering for Information Dominance: A Human Factors Perspective; Tech. Report AL/CF-TR-I 996-01 59.

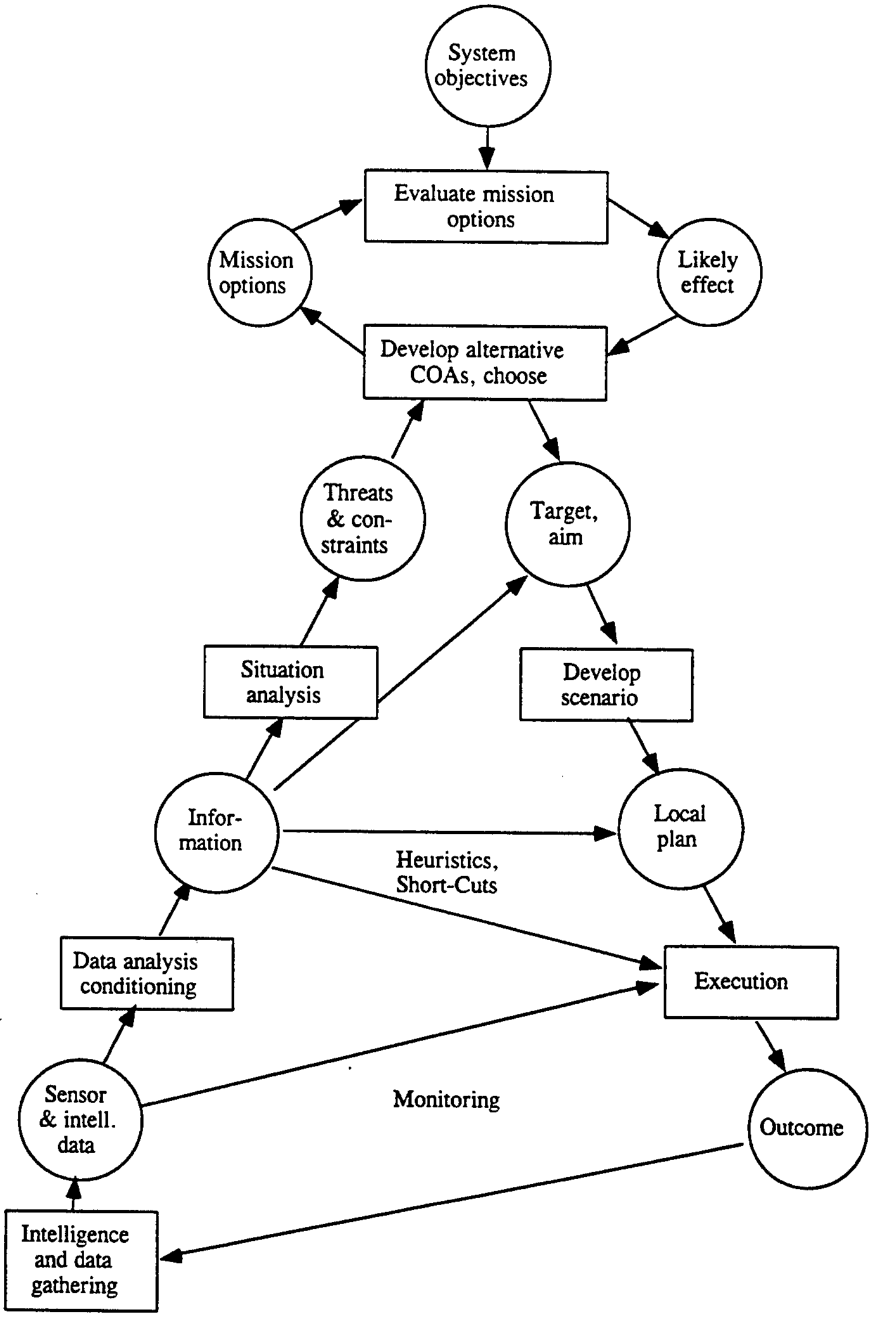

Figure 9.1. The decision ladder representing the sequence of basic information processes in a decision task together with a number of heuristic short-cut paths.

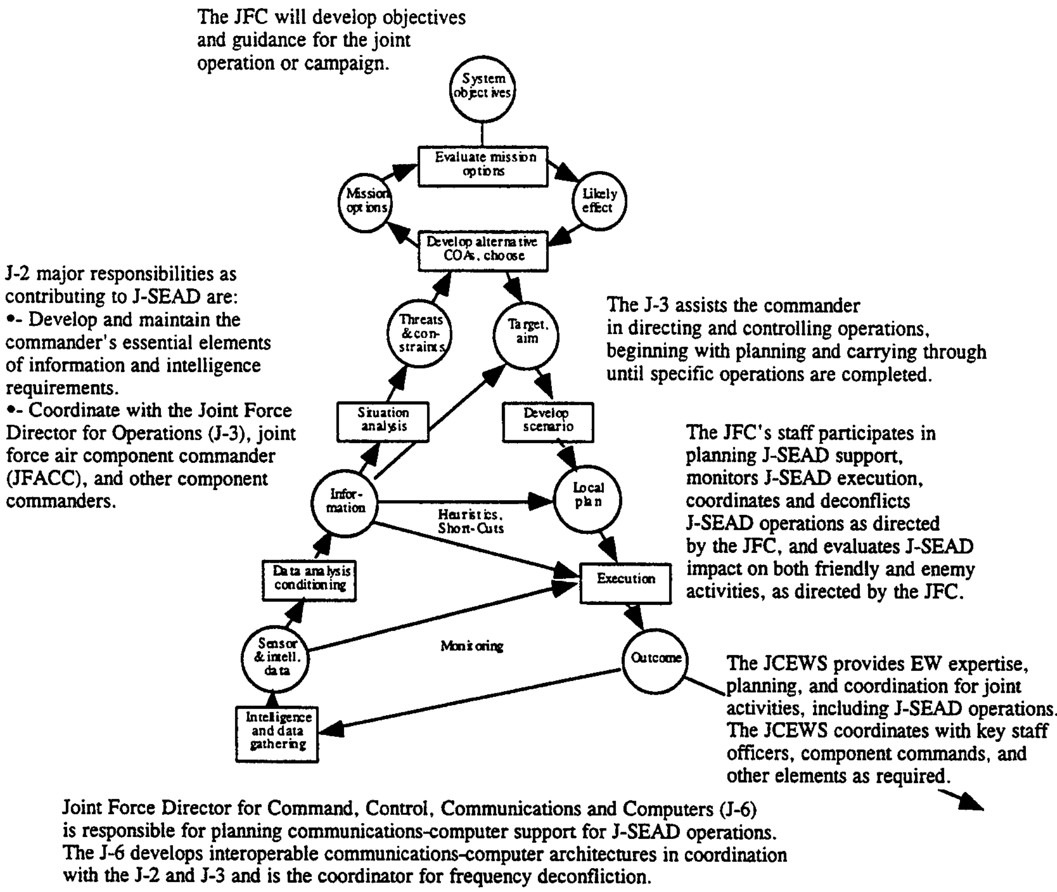

Figure 9.2. A schematic illustration of the division of activities with reference to the involved decision making functions.

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10. Decision Strategies

Another benefit from the decision ladder diagram is that it separates different *decision* processes for which alternative *information* processing *strategies* available to humans and computers. In SEAD work, the situation assessment is a crucial decision elements for which several very different cognitive strategies are applicable, such as induction, hypothetico-deduction, decision table search, recognition, etc. These strategies have very different requirements with respect to processing model and capacity, time, data volume and prior experience and these requirements are important criteria for defining an effective distributed, and cooperative decision making organization.

For example, the analytical, systematic planning strategy is very data and time demanding and not suited for decision making in a fast pace, dynamic situation, for which recognition or decision table search will be more suited. Accordingly, analyses of the decision making of fighter pilots by Amalberti[30] showed that their level of expertise is closely related to the size of the repertoire of possible flight mission scenarios they anticipated during pre-briefing and for which they prepared proper cue-action sets. This aspect is particularly important for UAV control, considering the considerable time delay between the operator decisions and the aircraft response. Considering the game like situation, and the attempt of opponent to destroy the craft, a complex cooperation is found between operator planning and automatic control of the craft. On one hand, preplanning of flight scenarios by an operator is necessary, as is the case for fighter pilots. On the other hand, flexibility should be left the auto pilot to respond to threats. That is, the auto pilot must be able to classify situational cues and to navigate around prototypical threats and constraints, identified and defined by the tele-operator. The use of the decision ladder to represent this complex cooperation is outlined tentatively in figure 10.1.

For decision task such as monitoring the complex communication system involved in SEAD, the work found on control of communication satellites should be consulted. Similarly, for vehicle maintenance and for diagnosis and control of onboard technical systems, work within the process control should be considered. [31]

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[30] Amalberti, R. and Deblon, F. (1992): Cognitive Modeling of Fighter Aircraft's Process Control: A Step towards an Intelligent On-board Assistance System. Int. Journ. of Man-Machine Studies, Vol. 36, No. 5 (May), pp. 639-671.

[31] For an overview of industrial diagnostic strategies, see J. Rasmussen and W. B. Rouse (Ed.): Human Detection and Diagnosis of System Failures. Plenum Press, New York, 1981

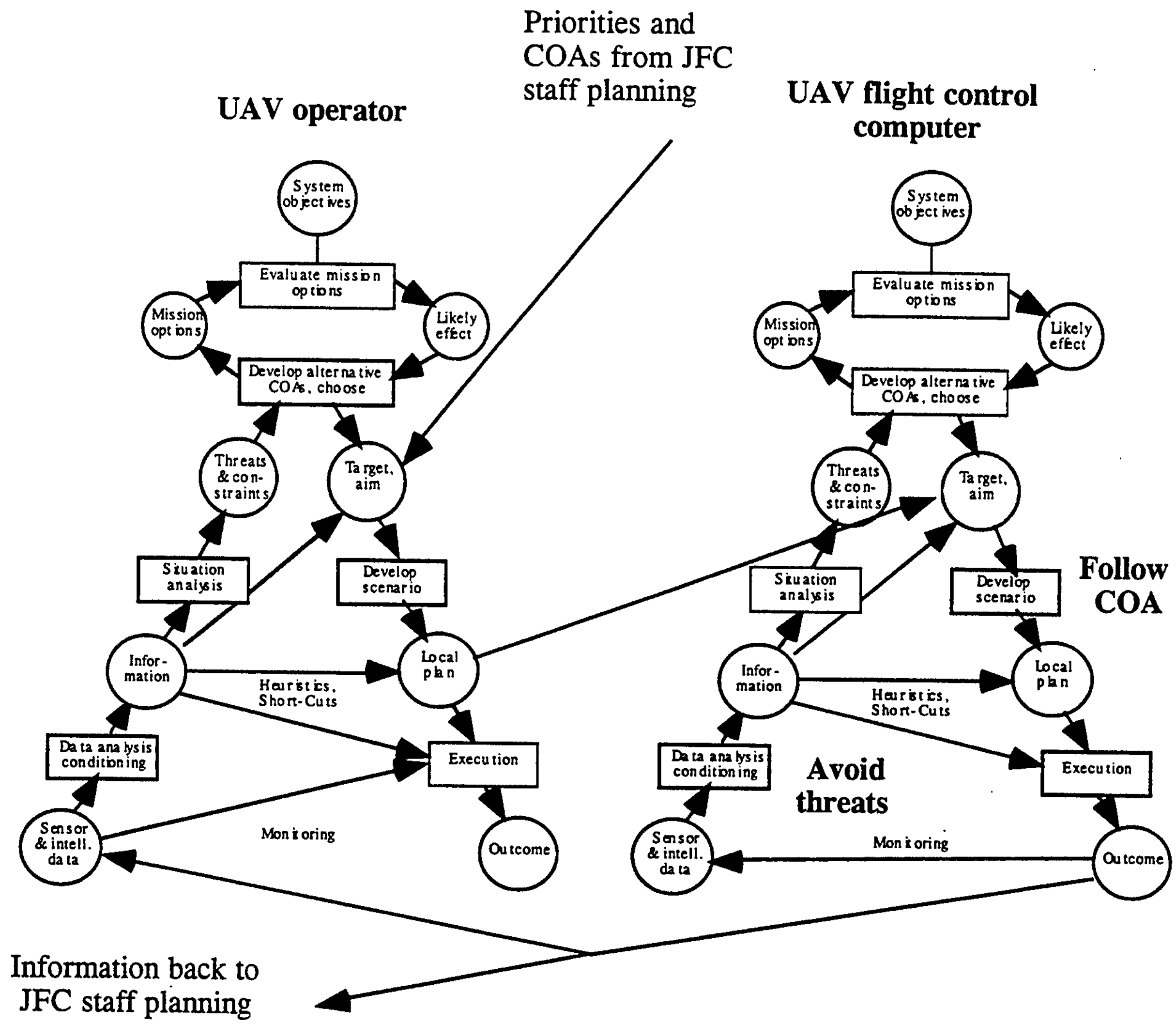

Figure 10.1. The distribution of decision functions between the auto-pilot of a UAV and the remote controller.

11. ALLOCATION OF DECISION ROLES

In the present context, we consider a work space as a loosely coupled assembly of processes and functions, controlled and coordinated through the activities of cooperating actors. Thus the work organization is a distributed, adaptive control system and the aim of work analysis is to identify the mechanisms that shape this organization and govern the allocation of functions to individuals.

The characterizations of organizational structures and processes can range from stable and formalized to flexible and dynamic, and analyses of work organizations have pointed to the need for a framework for modeling the division and coordination of work that is capable of capturing the mechanisms behind organizational adaptation to change. In the following discussion, the term 'organization' does not refer to stable groups of people as they appear in organizational charts but instead to the relational structure necessary to coordinate the activities of individuals and teams.

A cooperative system involves many forms of social interaction. To cope with this complexity, it is useful to distinguish (1) the system of work as a functional organization for coordinating activities in a loosely coupled work space from (2) the social organization of the relationships among actors. Following this point of view, two organizational aspects are considered at different levels of analysis:

1. The functional work organization required to coordinate activities as governed by the control requirements of the work space. This functional organization will determine the *allocation of roles* to the individual actors and the *contents of the communication* required for coordination.

2. On the other hand, the control requirements of the work space leave many degrees of freedom for the role allocation and, therefore, the role configuration chosen by or imposed upon the individuals and/or teams also depends on the style and formal strategies of a management, - which also influence the *form chosen for the communication* and social interaction within the functional organization. The form depends on the conventions and formal constraints chosen for the expression of this communication.

11.1 Functional Work Organization

The control requirements of a work domain change over time as will the functional work organization. A particular division of activities and, consequently, a functional work organization will evolve for each situation depending on the competencies of the actors, the technology of the work domain and on the external environment of the organization. Studies show that, even in traditionally tightly controlled organizations such as the military and high hazard process plants, the actual cooperative structure changes dynamically to match the actual circumstances and therefore a framework for modeling must be able to capture this adaptive feature. The introduction of UAV systems for reconnaissance and combat has been considered a rather local issue, judging from simplistic slogans[32] such as: "Better to bring the pilot to the information than the information to the pilot" and "Keep the pilot's brain in the cockpit, but leave the rest of him at home." Actually, the introduction of the UAVs with specialized ground control and analysis groups with several subject matter experts (data analysts, meteorologists, maintenance technicians, etc.) will imply a potential for a fundamental change in functional mission organization.

The need to reconsider the organization for military RSTA operations was explicitly mentioned in the C4I discussion[33] quoted in the introduction (Section 2, page 4):

> "Not surprisingly, synchronizing diverse RSTA capabilities to support operations involves complex coordination and planning considerations. During this process, the Commander and his staff must ask themselves: Are these assets best employed in general support of the MAGTF [i.e., Marine Group Task Force], direct support of subordinate units, or both? Will these assets fall under G2 or G3 purview, or should a Commander-designated board conduct oversight and management? What relationship must be established, what coordination effected between organic and non organic RSTA assets and the Surveillance and Reconnaissance Center (SARC), the Combat Intelligence Center (CIC), and the Combat Operations Center (COC)? Who orchestrates the coordination for RSTA planning, and who provides the sanity check on how well the collection strategy supports operations? Given that diverse RSTA operations occur simultaneously within the battlespace--keyed to support a range of users from decision makers to "shooters"--what parameters must define the information flow, and who should oversee the dissemination process to ensure usable intelligence reaches the Major Subordinate Commands?"

The answer to such questions will be that the coordination structure depends dynamically on the situation, and the basic question for efforts to shape an effective functional organization will be to identify the criteria that dynamically influence its structure and, therefore, should be considered when designing support systems.

In an actual work situation, adoption of work roles by the individual actors depends on several criteria:

Norms and Practice. In stable systems with a long prehistory, the formal role configuration is often closely related to the actual and frequently hierarchical

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[32]See AGARD Conference on Subsystem Integration for Tactical Missiles (SITM) and Design and Operation of Unmanned Air Vehicles; Ankara, October, 1995.

[33]Reconnaissance, Surveillance, and Target Acquisition Collection Planning--Embedded Within the MEF Intelligence and Operations Cycles. Authors: Intelligence Doctrine Working Group; May 1995; Chairman: Major J.C. Dereschuk, United States Marine Corps (www.clark.net/fas/irp/eprint/derescheck.htm).

organizational structure and the corresponding social status rankings. Very often, this formal structure poses very strict constraints on the actual work allocation, in particular when strict boundaries between professions are established through e.g., military formalisms, union agreements.

Load-sharing. Frequently, division of work is governed by efforts to share work load, - both formally during work planning and informally and dynamically during the work process itself.

Functional de-coupling. This criterion reflects efforts to minimize the necessary exchange of information among actors. This criterion is particularly important in dynamic, fast acting systems for which the control requirements can be organized according to sub-units with internal high capacity-fast time response requirements, but with less and slower mutual interaction. Controllers can then be organized in a hierarchical structure according to capacity and time requirements, which normally will be reflected in role allocation. Judged from the discussion in the JTTP doctrine, this criterion has been important for the SEAD organization.

Competency. The competence required for different tasks clearly influences the division of work.

Information access. In stable, work domains and during routine situations, span of attention of the actors, and the information access the are given, can be rather limited. However, in a changing domain and during unfamiliar situation, this should not be the case. The potential for discretionary problem solving depends heavily on the width of the information window available to the decision. A horizontally wide window is necessary for dynamic coordination and a vertically wide window is necessary for selecting proper means-ends relations.

Safety and reliability. For work in a domain posing a hazard to staff members or resources, safety criteria, such as adequate redundancy, are governing cooperation. In this case, critical functions are allocated to more than one individual or team so that different individuals independently test or verify the performance in a particular function. The studies by Rochlin et al.[34] mentioned below clearly demonstrate the importance of functional redundancy in the evolution of highly reliable military organizations.

The criteria listed here are often competing and their influence change with time as governed by the control requirement of the work space. For instance, even in a military organization governed by formal ranks, the control requirements of the operations occasionally take over and shape the cooperatives structure. The work of Rochlin et al. demonstrates the pronounced ability of the organization on an aircraft carrier to shift between (a) a formal rank organization, (b) a self-organizing 'high-

[34]Rochlin, G. I., La Porte, T. R., and Roberts, K. H., (1987): The Self Designing High Reliability Organization: Aircraft Carrier Flight Operations at Sea, Naval War College Review, Autom 1987.

tempo' work coordination across ranks and organizational units and (c) a flexible emergency organization responsive to the immediate requirements of the actual situation. In such cases, the dynamic control requirements overrules the formal, rank organization found in less stressed periods.

The findings from this aircraft carrier study is a clear argument for the need to study the evolution of an effective functional organization when UAVs are introduced into a critical, high tempo, military mission. The division of work during planning of an AOR/JOA SEAD mission is shown in figure 11.1 with reference to the discussion in the JTTP[35] doctrine. As shown in figure 7.4 this structure reflects domain oriented architectural features as well as decision-function oriented features (see figure 9.2). This architecture reflects a preplanned, normative organization, and a study of the actual, functional organization will be required to ensure adequate flexibility of the command-and-control design. The study of the actual, dynamic sharing of work can be based on interviews for creation of a representation of the communication links, as shown in figure 8.2. From these lists, a communication matrix (figure 11..2) can be developed and serve[36] an identification of the cooperative structure.

A recent study of the functional organization oriented toward a domain oriented architecture in equipment design[37] (see figure 11.3) has been based on interviews of substance matter experts and is a useful source of methodological inspiration. Also the CDT studies[38] at the Armstrong Lab. are important in this respect.

Recent accidents present clear examples of the conflict between operational criteria such as sharing workload, and more latent criteria such as procedural redundancy for protection against rare occurrences. Adaptation of the role allocation and the coordination of work to local criteria during normal conditions have lead to severe consequences under unhappy circumstances. In the Clapham Junction case[39], for instance, safety checks following modifications of signal system wiring were planned to be independently performed by three different persons, a

[35]Joint Pub 3-01.4 "JTTP for Joint Suppressions of Enemy Defenses (J-SEAD)" 25 July 1995, Joint Chiefs of Staff.

[36]For details, see Rasmussen, J., Pejtersen, A. M. and Goodstein, L. P. (1994): Cognitive Systems Engineering. New York: Wiley.

[37]Annelise Mark Pejtersen, Diane H. Sonnenwald, Jacob Buur, T. Govindaraj and Kim Vicente (1995): The Design Explorer Project: Using A Cognitive Framework to Support Knowledge Exploration. International Conference On Engineering Design; ICED 95; Praha, August 22-24, 1995

[38]Whitaker, R. D., Selvaraj J. A., Brown, C. E., and McNeese, M. D. (1995): Collaborative Design Technology: Tools and Techniques for Improving Collaborative Design. Wright-Patterson AFB: AUCF-TR-1 995-008 6.

[39]HMSO (1989): *Investigation into the Clapham Junction Railway Accident*. The Department of Transport. London: Her Majesty's Stationary Office, 1989.

technician, his supervisor, and the system engineer. Work force constraints and tight work schedules, however, led to a more "efficient" division of work. The supervisor took part in the actual, physical work and the independent check by him as well as by the engineer was abandoned. In addition, the technician integrated the check (a "wire-count") into the modification task itself although it was intended to be his final separate check. In short, adaptation to a more effective division of work under time pressure causes the redundancy required for protection against unusual events to deteriorate.

11.2 Architecture of Social Interaction

The cooperative structure responding to the control requirements of the operations clearly specify the contents of the communication. On the other hand, many degrees of freedom are left with respect to the form of communication serving the coordination among actors, depending on the conventions chosen for social interaction. Various structures of social organization are possible and they may be more or less independent of the task and the role configuration principle adopted as well as the characteristics of the work domain.

Traditionally, the formal, social organization is hierarchically organized corresponding to business professions or military rank. Then one level of decision makers evaluates and plans the activities at the next lower level. This hierarchical structure has its roots in the military command, control and coordination paradigm. Even within this structure different coordination, or management styles, are possible depending on whether the communication downward through the system is based on the communication of procedures (the bureaucratic model), or on passing down objectives (the adaptive model).

Recently, a clear trend is toward more flexible, 'learning' organizations to be able to respond more effectively to the present fast pace of change. Since several structures of social organization properly can serve the control requirements of a given domain, the basic difference is the *form* of communication chosen to serve coordination, that is, whether information is passed as neutral information, advice, instructions, or orders. The effective way of influencing the social organization independently of the work organization will be through constraints and conventions for communication.

As mentioned above, the structure of coordination within a team operating a technical system will normally be forced by the internal coupling and control requirements of the system. In less constrained cooperative task situations, team cooperation will be influenced more by the social dynamics within the team, but still the cooperative structure can change dynamically depending on the characteristics of the different phases of a task.

This dynamic nature of the social organization has been studied by McNeese and his group.[40] Another illustrative example is described by Sonnenwald who analyzed the cooperation within various industrial design teams.[41] Sonnenwald identified several characteristic phases of a design project and found characteristic social patterns of cooperation for each phase. For each, different social roles were adopted by team members, some similar to those guided by the criteria for division of work discussed above and related to the domain and interests they represent ('consumer', 'technician', 'backer'), some related to their social role and initiatives in the form of communication ('facilitating actor', 'intergroup star', intragroup star', gate keeper).

For example, in design situations which took place in less constrained environments (where team members could structure their patterns of behavior somewhat independently of the environment) a 'facilitating agent' emerged. The facilitating agent fostered communication among team members and helped them negotiate conflict. This enabled the team to complete tasks that required a consensus among team members who had different, and conflicting, perspectives. In this way, a social role, a facilitating agent, aided task completion.

This kind of study of the organization evolving in UAV operation will be very informative for the design of support systems.

[40]For a methodological review see Whitaker, R. D., Selvaraj J. A., Brown, C. E., and McNeese, M. D. (1995): Collaborative Design Technology: Tools and Techniques for Improving Collaborative Design. Wright-Patterson AFB: AUCF-TR-1 995-008 6.

[41] Sonnenwald, D. H. (1994): Supporting Knowledge Exploration in the Design Process. In: Proceedings of the ITD 94 East-West Conference on Information Technology in Design. Moscow. International Centre for Scientific and Technical Information. pp.175-184.

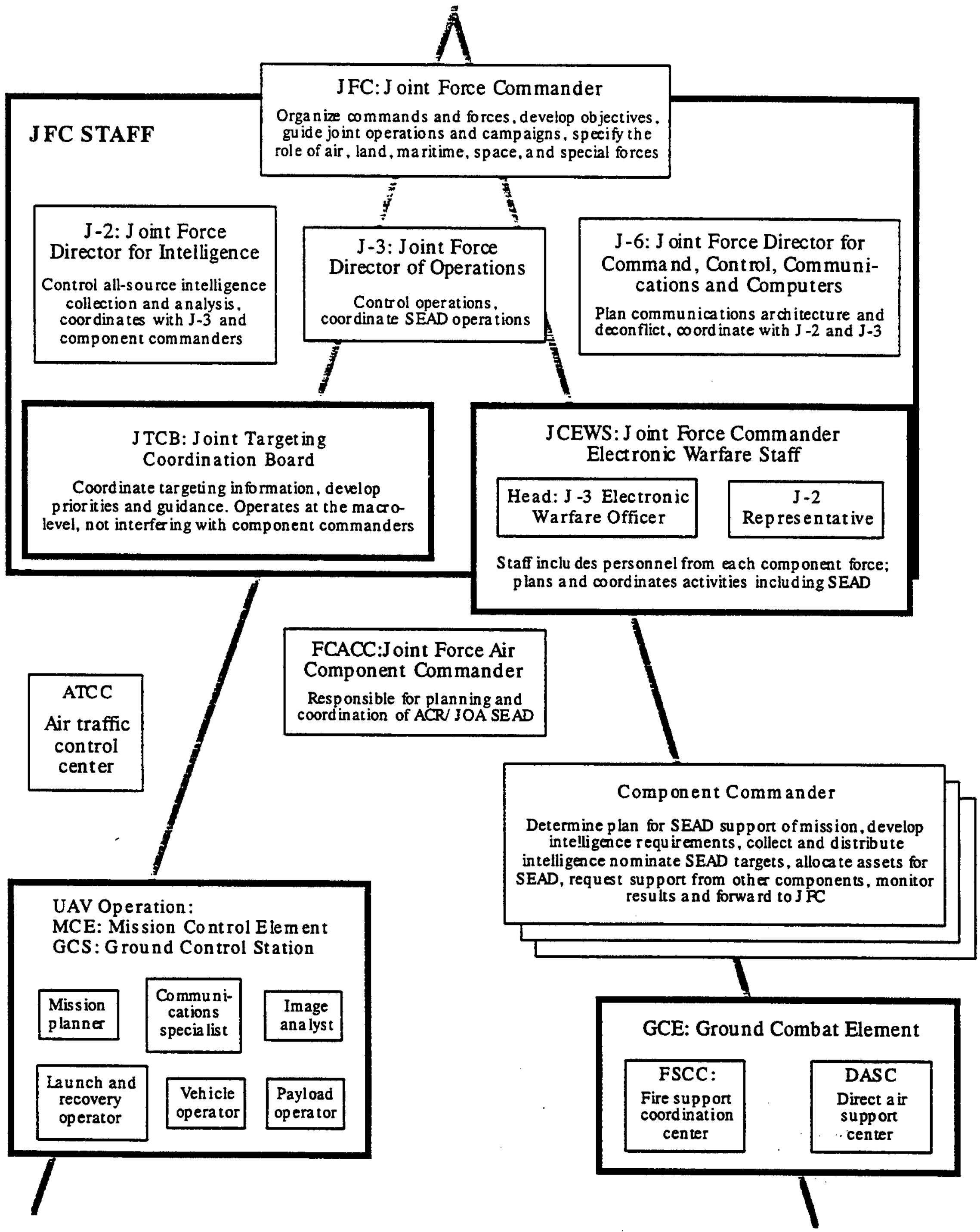

Figure 11.1. The formal hierarchical organization of actors in AOR/JOA SEAD planning and execution.

Information Receiver

Information Source

Actor	A	B	C	D	E	F	G	H	I	J	K
A	O										
B		O	V	V	V						
C		V	O	V	V						
D		V	V	O	V						
E		V	V	V	O	V	V	V	V	V	
F					V	O	V	V	V	V	
G					V	V	O	V	V	V	
H					V	V	V	O	V	V	
I					V	V	V	V	O	V	
J		V								O	V
K											O

Figure 11.2. The actual work organization can be identified by means of a communication matrix. For each of the relevant communication links, information content and form should be identified and a "connectivity matrix" developed as shown. By means of column-row manipulations, a matrix with the elements concentrated around the diagonal can be found. This representation of the communication structure identifies the groups needing close cooperation for a particular task situation. The connectivity matrix analysis can be a very effective tool for matching a formal organizational structure to the natural group formation.

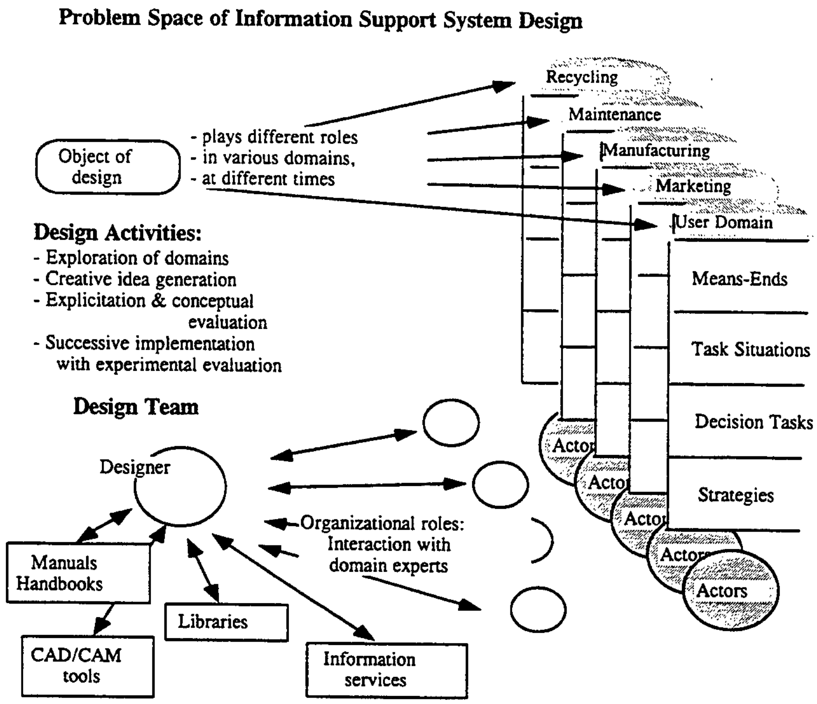

Figure 11.3. The figure illustrates the context of design, that is, the design team, the domains of activity involved, and the information sources to be accessed during the design process.

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12. Coupling of Decision Makers to Problem Space: Interface Design

According to the framework discussed in the previous sections, an effective coupling of actors to their problem space is created by *making visible the ecology of the work space.* Operation of a system depends on purposeful changes of the state of its internal processes. Such changes are not made directly by the actors. Instead, their actions serve to set the constraints of active forces within the system which then bring about the intended changes. As described by the means-ends representation, these active forces have different sources. Some have a causal basis (laws of nature), others have intentional basis (mission objectives, intentions of cooperating actors) and, finally, some have formal basis (rules and regulations). The opportunity to plan activities and to act depends on knowledge about such *internal behavior shaping constraints* that control the system's dynamic behavior and about the *parameters sensitive to change* by goal directed acts. In addition, knowledge about constraints in terms of limits of acceptable or safe operation are important for effective operation.

It follows that it is a key design issue to create an information environment for the controllers that makes visible the ecology of work, that is, the internal behavior shaping constraints, and supports direct perception of the state of the world in the light of the current goals, as well as the boundaries of the acceptable performance.

In a world of dynamic requirements, a map of the deep structure of a system supports navigation more effectively than route instructions.

Implications for Interface Design

This discussion shows that the basis of the design of an effective decision support system must be derived from the causal and intentional constraint underlying the operative system design, that is, *the content of interfaces is defined by the means-ends and functional relations represented by the 'requisite variety' described by the abstraction/decomposition map.*

The design problem is *not* to match a display format to the mental models of the operators[1] but to design an interface that forces operators to adopt a faithful mental model of the design constraints in a way they can *directly perceive and operate on* the constraints so as to bring the system into the goal

[1]See also Kim Vicente: Should an Interface Always Match the Operator's Mental Model? CSERIAC Gateway VIII, 1, 1997.

state and/or prevent it from entering unacceptable or dangerous states. This requirement presents additional specifications for the *form* to choose for display formats.

In computer based work stations, the direct perception-action interaction with a physical world for which humans have adapted through ages is replaced by operation upon a 'virtual work ecology.' As long as work conditions are stable through time, and activities can be based on an established practice with stable cue-action correlation, humans can adapt to nearly any kind of interface representation and many varieties have been developed for tools introduced in particular tasks during the history of computers, such as command interfaces, metaphorical interfaces, menu-systems, etc.

A major interface design problem appears, however, when interface systems are to be effective for systems with variable control characteristics depending on system states and disturbances and involve discretionary decision making during unfamiliar and high tempo situations as it is the case for SEAD command and control systems. In that case, control cannot rely entirely on cue-action matching as specified in a preplanned COA. Then a representation of the internal functional structure of the system is required to support local interpretation. Any control action activated through a work station serves to change the internal, causal or intentional constraints to let them bring system state to the intended target. The interface should then represent the actual state of affairs in the work space in a way comparable to a representation of the intended or the useful state defined by the current goal, together with the situation dependent "affordances" i.e., the options available for action on the constraints, as well as the boundaries of acceptable operation as defined by the physical design or by policies, practices, or regulations. This is the objective of ecological interfaces design.[2]

Design of ecological interface systems can be structured into separate design issues, related to the *content* and the *form* of a graphic display. Other issues should be explicitly considered, such as a transformation from the quantitative,

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[2]Vicente, K. J. and Rasmussen, J. (1992): Ecological Interface Design: Theoretical Foundations. IEEE Trans. SMC, Vol. 22, No. 4, pp 589- 607, July/August 1992.
Rasmussen, J. and K. J. Vicente (1990): : Ecological Interfaces: A Technological Imperative in High tech systems? International Journal of Human Computer Interaction 2(2)93-111 (1990)
Vicente K. J. and Rasmussen, J. (1990): The Ecology of Human-Machine Systems II: Mediating "Direct Perception" in Complex Work Domains. Ecological Psychology, 2(3), 207-249.
Rasmussen, J. and Vicente, K. (1989): Coping with Human Errors through System Design: Implications for Ecological Interface Design, International Journal of Man-Machine Studies, (1989) 31, 517-534.

relational representation normally applied for formal system analysis into a qualitative, causal representation underlying human reasoning, as well as display organization to support navigation in a complex interface system including a large number of display windows.

12. 1. The *Content* of a Display

The *content* of the display interface should faithfully represent the constraint pattern and the actual state of the system with reference to this constraint pattern. This information can be defined at all the various levels of the means-ends network, each having its own particular formulation depending on the related source of regularity.

The specification for display content design will vary with the language used for representation at the different levels originating in the various professions involved in system design and operational planning. The abstraction-decomposition map defines a shared knowledge base from which information should be available in the kind of representation required, depending on the decision makers role in the work space (figure 7.12) or the planning process (figure 9.2) with consideration of the relevant mental strategy.

As discussed, the interface should give a faithful representation of the actual state of the system with reference to the intended or normal state and to the boundary of the acceptable operation. Furthermore, the internal behavior-shaping constraints should be represented with explicit reference to points sensitive to control.

The symbols to be used for representation of the actual and the intended state of affairs depend on the work situation of the decision maker. The decision ladder can be used to identify those 'states of knowledge' that are relevant for exchange among various actors, depending on the overall situation. Figure 12.1 demonstrate how different states in the basic decision sequence are used for communication for AOR/JOA SEAD planning and as short-cut links for the more close viewer-shooter connection that is often required (e.g., for localized and opportune suppression).

12.2. The *Form* of a Display

The visual coding, the *form*, of the display should create a 'virtual ecology' of work matching the users' perception-action capabilities as well as mental simulations involved in problem solving, that is, it should be chosen to support the interpretation at three levels of cognitive control at the discretion of a user in each situation:

Skill-based control: The interface should present a world of graphic objects in a virtual topography directly matching the natural perception-action abilities of humans. Therefore, the spatial-temporal characteristics of the display should support skill-based operation during routine situations. For this mode of interaction, the *spatial-temporal control loops must be intact* through the interface mediation. This is particularly important for remote vehicle control.

Rule-based action: During familiar choice situations, the interface should allow formation of convenient, but reliable *cue-action responses*. For this, a display should integrate all the behavior relevant constraints of a work situation into a perceptual pattern, that is, it should include *all relevant attributes* to make the emerging cues for action *complete,* that is, situation defining. Incomplete, but convenient cues very likely will lead a user into a behavioral trap when system properties change and make familiar cues invalid. It is well-known, that reliance on under-specified cues is one of the most frequent categories of action errors in systems having conventional control interfaces.

Knowledge-based reason: For unfamiliar situations, the display should serve as a faithful, externalized symbolic model to support *mental experiments*. Since natural language explanations and arguments are framed in terms of objects and their interaction in terms of events within a background topography, it is important to code information into a symbolic object world for direct visual manipulation.

Given the aim to design interface representations that guide system users to adopt effective mental models supporting discretionary decision making, careful consideration should be given the visual representations used by designers to explain their design intentions and the functions of their solutions to fellow designers and students. Within the different professional domains involved in system design, visual representations in the form of figures and diagrams have been used through decades or even centuries to communicate with colleagues and students, and the result of this evolution of visual forms is an important source of ideas for interface design. The productive functions of a system and the means chosen for their control (whether automatic or manual) are considered by designers as one integrated whole. When system users are required to apply discretionary decision making, they are in fact taking part in the design of control strategies, closing the degrees of freedom left over by the initial designer. The representations used by designers are therefore a good source for ideas for the form of displays for system operators requested to improvise when conditions change.

In addition to such considerations, it is important that the language used to express the content at the display surface is acceptable to the relevant user groups. Several highly developed conventions directed toward different population groups have evolved in the past for specific applications, such as research and teaching (pictures, maps, diagrams), guidance of behavior (traffic signs, icons), computer use (desk top metaphors), etc. For displays, the forms chosen for visualization should respect such established traditions to avoid conflicts.

12.3. Transformation from Relational to Causal Representation

An important interface design issue when choosing the form of the presentation then is to integrate the raw measuring data into higher level objects, states, and events that match the conceptual language and the level of abstraction applied in the users' causal reasoning.

In many cases, professional information processing is based on formal models in terms of quantitative data and mathematical relations. This is the case when the optimal state of operation of technical system are determined, such as e.g., in control of aircraft. The measuring and control systems are therefore designed to make it possible during operation to ensure that these quantitative relationships are optimal. That is, the fundamental basis of the instrumentation and the choice of measured variables is determined by the *quantitative, relational models underlying system design and process optimization.*

In contrast, the natural language reasoning applied by human decision makers depends entirely on a *causal model in terms of objects in a background interacting through events.* Therefore, the measured variables and the relational structure governing their interaction must be converted at the interface to a set of symbolic objects interacting through events in a virtual environment. The interface therefore should present a map of a symbolic landscape inhabited by objects -icons - representing states of processes, interacting mutually and with boundaries around territories of varying operational significance. This is important, not only to support the reasoning by an individual user, but also to give cooperating users an opportunity to point at and to discuss an external model.

This is actually the function of all engineering diagrams used for design and for explaining concepts and processes for students. For ages have the optimization of the operation of steam engines and planning of their maintenance been based on heuristics related to pressure-volume diagrams of cylinder performance (see figure 12.2), and complex control systems have been synthesized by heuristic manipulation of 'root-locus' plots (see figure 12.3). We will return to more examples later.

12.4. Support of Navigation in the Interface System

As Woods[3] has pointed out, a problem in design of complex system interfaces is to support users' navigation through the many interface windows available in large scale systems.

This issue of navigation is basically not a question of navigation in the interface system, but in the shared knowledge base, represented by the global means-ends map. The navigation in the map can be structured from the analysis of the 'prototypical' situations identified during activity analysis which serve to identify the information windows to the map which are likely to be relevant for the individual situations. Effective navigation in this map then depends on an indexing of the information items that reflects the relevant query formulations such as the what, why, how relations in figure 7.13. Good guidance for navigation also depends on a match of indexing corresponding to different useful retrieval strategies,[4] such as browsing in a knowledge base, analytical query formulation, or search by analogy.

Designing support system, the normal competence of the users should be carefully considered when selecting modes of guidance, an issue which often is not explicitly exposed. Thus, knowing the means-ends relations of a work system is part of the normal competence of professional system operators and navigation in the knowledge base can be guided effectively by visualizing the functionality of the system. A map of the means-ends options with indication of that display window that offers new information can therefore support navigation in the display repertoire. In experiments by Goodstein,[5] all displays had a small means-ends map indicating the display formats that had new, not acknowledged data. For the skilled operators this indication often was adequate for alarm diagnosis.

Experiments to design an interface system in which navigation is guided by the operators' competence with respect to the task structure during start-up of

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[3]Woods, D. D. (1984): Visual Momentum: A Concept to Improve the Cognitive Coupling of Person and Computer. International Journal of Man-Machine Studies, 21, 229-244

[4]For more detail see Pejtersen, A. M.: Design of intelligent retrieval systems for libraries based on models of users' search Strategies. In: 1986 IEEE International Conference on Systems, Man and Cybernetics. Washington, 1986.

[5]Goodstein, L. P. (1985). Functional Alarming and Information Retrieval; Roskilde, Denmark; Risø National Laboratory, Risø-M-2511.

a nuclear power plant is underway at JAERI,[6] Japan. The structure of the display repertoire and its use during the task is shown in figure 12.6.

[6]Tanabe, F., and Rasmussen, J. (1997): Simulator experiments with Ecological Interface Systems: A note for Discussion. Work in progress.

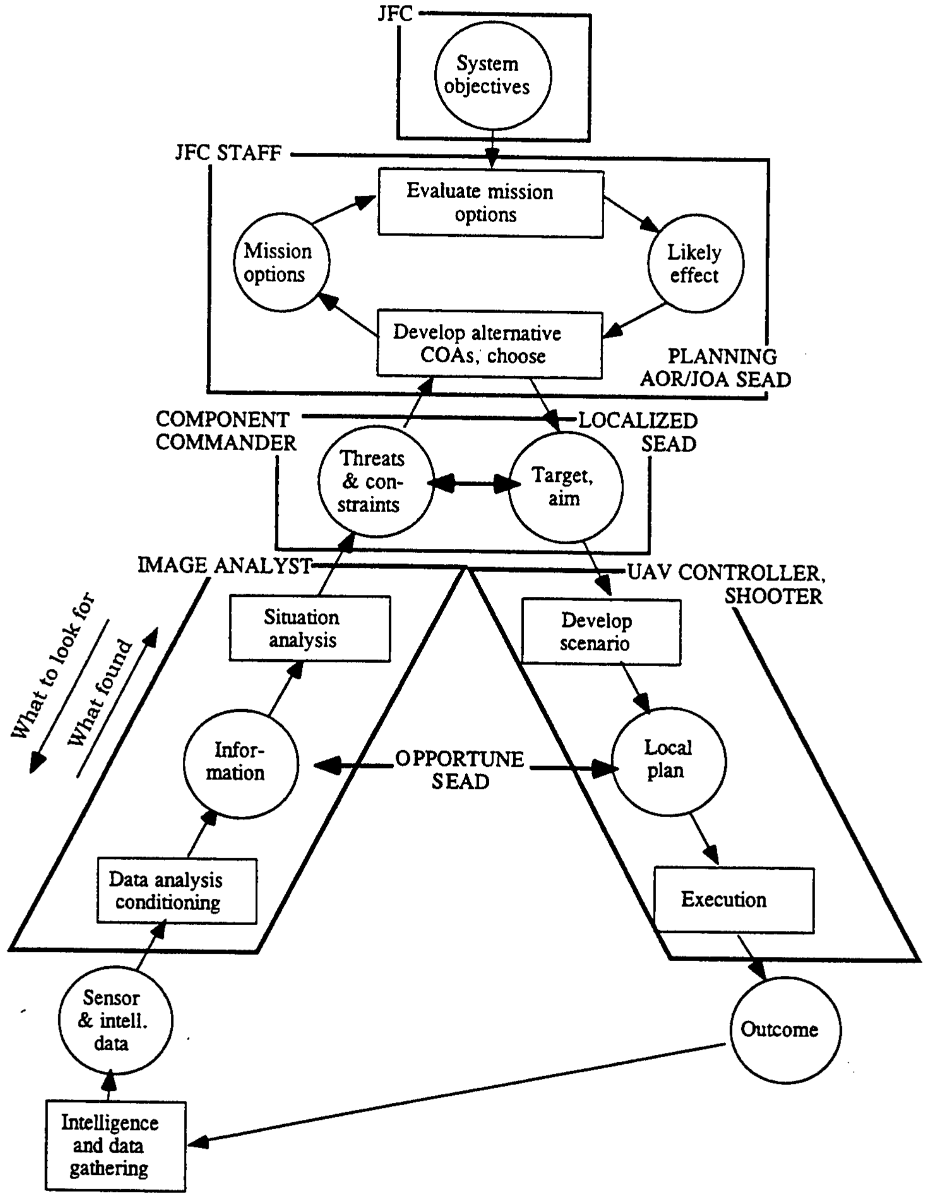

Figure 12.1. The decision ladder can be used for coordination of the different 'states-of-knowledge' relevant as communication points in collaborative SEAD planning and to identify states functioning as switch-points of communication depending on the basic SEAD scenario.

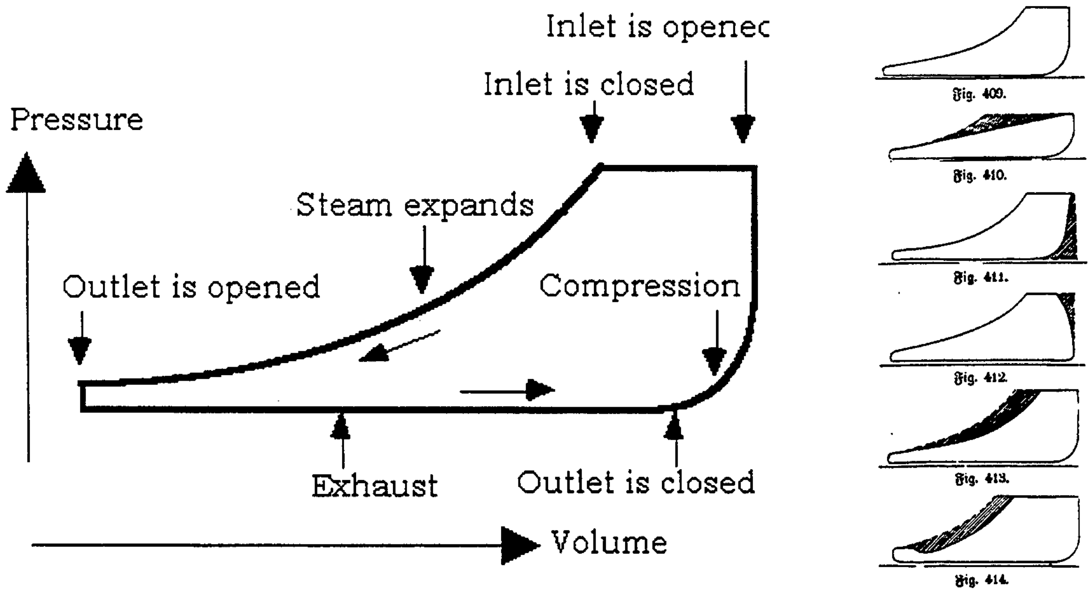

Figure 12.2. In thermodynamics, pressure-volume diagrams have been used to describe the work cycle of steam engines for more than a century and heuristics were developed by steam engine operators to select maintenance actions from the appearance of the shape of the diagram recorded by a needle tracing the pressure of the engine cylinder on a record moved by the piston stem, see figure to the left. The inlet valve is opened on top of the piston stroke, high pressure steam enters and moves the piston. Later the valve is closed, the steam expands and the pressure drops while work is done. At the bottom of the stroke, the outlet valve is opened for exhaust by piston reversal. Just before top position, outlet valve is closed, and steam is compressed. The area within the curve represents work done by one stroke. Multiplication by the number of revolutions per time unit gives the output horsepower level of the engine. Letting the steam expand to a low pressure before exhaust and compressing residual steam to inlet pressure before opening inlet valve give a very smooth and economic operation. If on the other hand, high torque is required as for start of a train, the inlet valve is open through the entire down stroke, resulting in high power and very noise performance. As is the case for EID in general, the graph reflects the internal relationships and constraints of the work process and, at the same time, invites to adoption of cues for action. The right hand side of the figure shows the cues for different maintenance tasks adopted from a mechanical engineering textbook dating 1912.[7]

[7] Reproduced from Häntzschel-Clairmont, W. (1912): Die Praxis des Modernen Maschinenbaues. Berlin: Verlag von C. A. Weller.

Points to use fo quick-draw of root locus:

① location of the open-loop poles
② parts of σ axis covered by loci
③ 'break-away points on σ axis
④ asymptotes for large values of |s|;
⑤ points where loci cross the jw-axis;

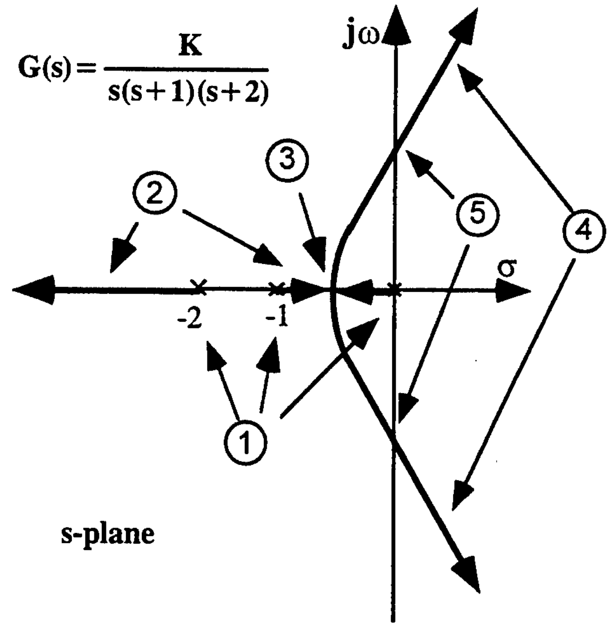

Figure 12.3. The figure shows the root-locus of a configuration of a control loop. It is used by control engineers to judge the stability of a closed loop without having to solve the complex equation of the closed loop: G(s)/ 1+G(s). The figure shows the particular features of the closed loop root locus that are easily found and used for determination of the general shape of the locus. By an increasing K value, two closed loop roots move to the right hand side of the jω axis and the system becomes unstable.

The figure illustrates how a problem stated in terms of quantitative, relational equations can be solved by manipulation of graphic symbols in a problem space.

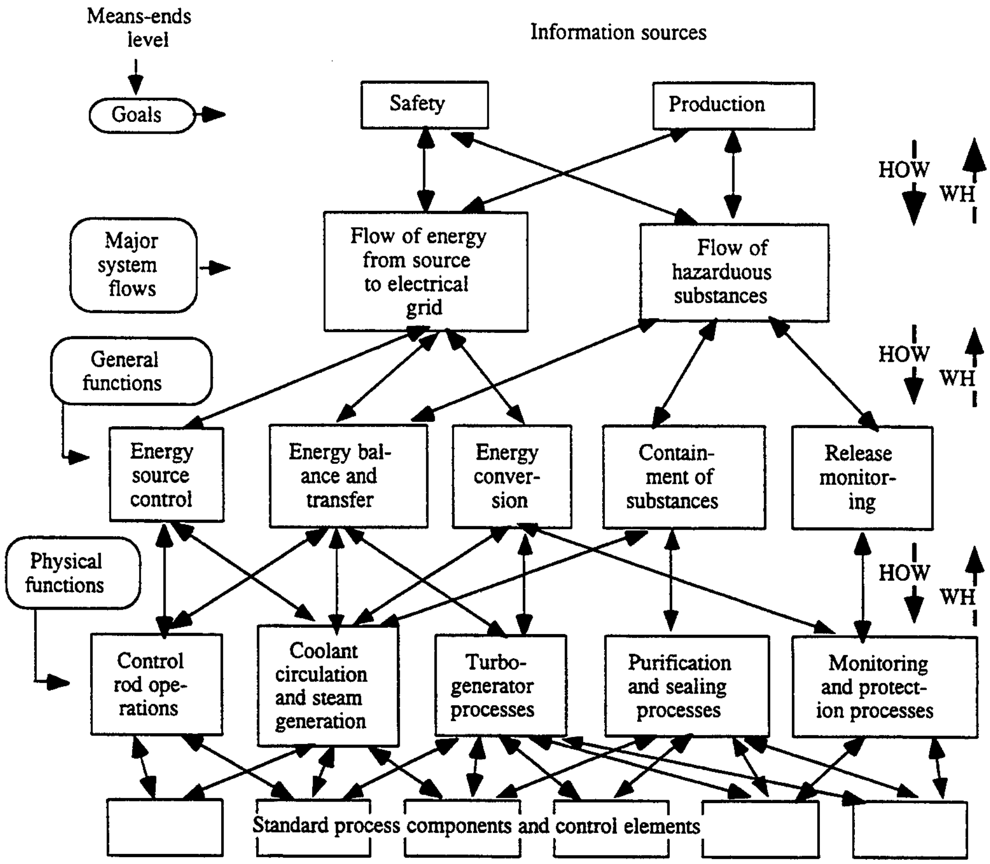

Figure 12.4. The figure shows the display formats available for control of a simulated nuclear power plant arranged according to the level of the means-ends hierarchy represented.[8]

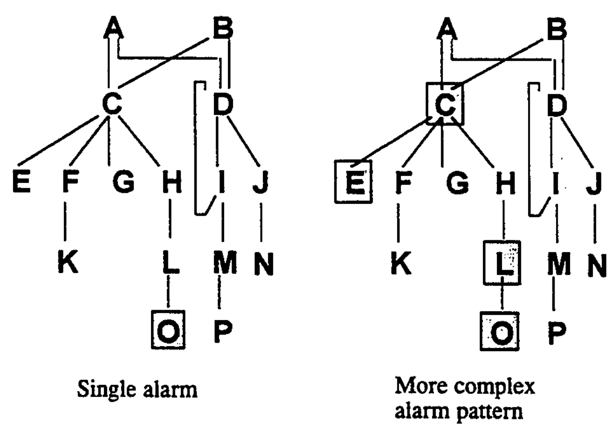

Figure 12.5. A short-hand visualization of the display repertoire of figure 12.4 with indication of the windows supplying new information (In this case, alarms).

[8] Figures 12.4 and 12.5 are reproduced from Goodstein, L. P. (1985). Functional Alarming and Information Retrieval; Roskilde, Denmark; Risø National Laboratory, Risø-M-2511.

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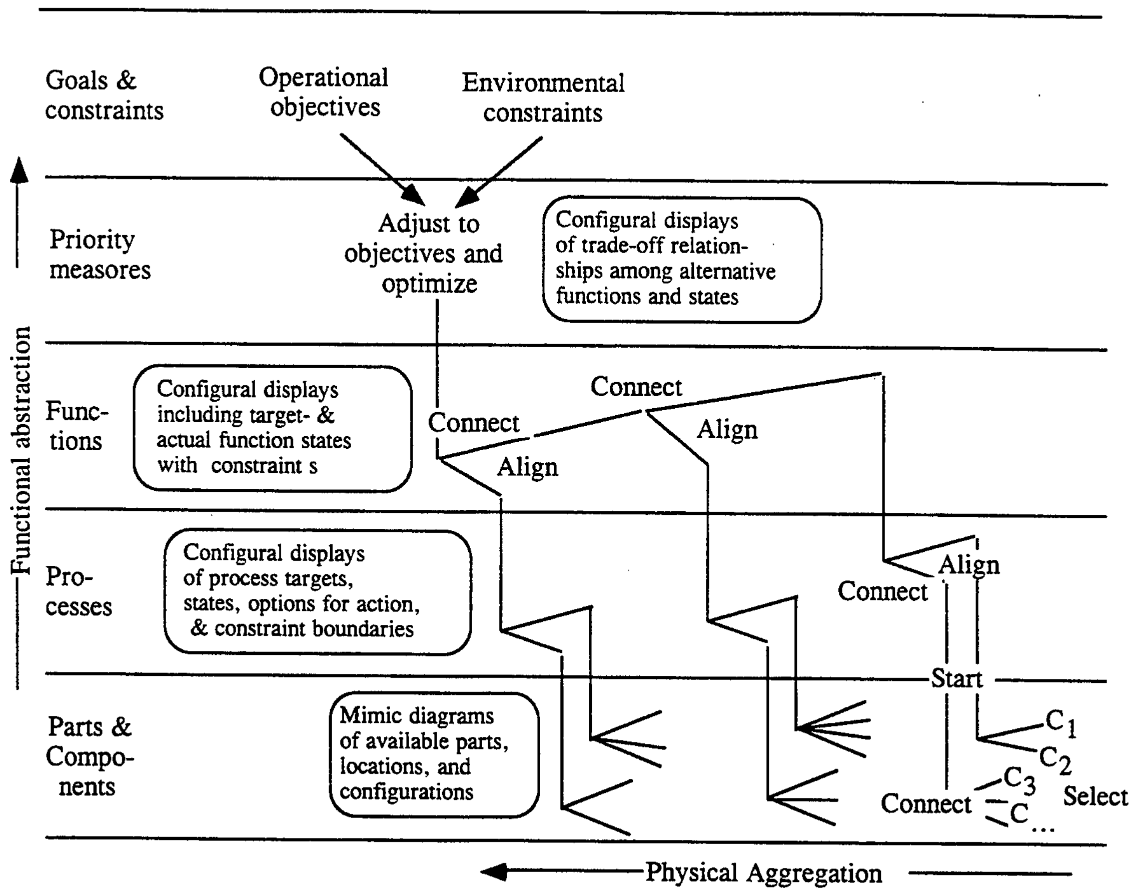

Figure 12.6. A map of the structure of the operations and the relevant types of representation for assembling a technical system from the available resources and starting its operation.

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13. A Means-Ends Map of Approaches to Visualization

Designing visual displays representing the deep structure of a system in a faithful way, that is, designing a 'virtual ecology' for direct manipulation of modern systems is a very complex process. Some kind of map of the design territory based on a taxonomy of visual representations will be useful.

Whether issues related to the design of the display content or the form are predominant in the process depends very much on the nature of the task situation.

Considering *operation of the technical equipment* of an aircraft or a process plant, it is a major systems engineering task to determine the necessary content of the individual displays, the integration of data into task-related windows to the global knowledge-base, and the representation of the intentional structure of the control strategies, see e.g., figure 12.3. Solution of these problems should involve the designers of the technical equipment and its control system rather than system users because, as mentioned, the problem is to guide the users toward the relevant mental model of the deep structure of the system - to shape and support their professional competence - not to match their heuristic from the past.

In contrast, for displays in support of *vehicle control*, a major issue is the match of the form to the perception-action characteristics of human locomotion. In the ecological interface literature, these two categories have each found their particular expression. Visual support of piloting aircraft has been studied in detail by Flach[9] and his group, while the control of aircraft support systems are studied Vicente's group.[10]

As a start to create a systematic basis for interface design guides, the means-ends network of figure 7.2 will be used to characterize some widely used representational forms with reference to interface design.

Different representations of functional relationships are used at the various levels of the means-ends network as shown in figure 12.3. Several conventions

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[9]Flach, J. M. (1997): Ready, Fire, Aim: A 'Meaning-Processing' Approach to Display Design. In D. Gopher & A. Koriat (Eds.) Attention & Performance XVII and Flach, J. M. and Dominguez, C. O., (1995): Use-Centered Design: Integrating the User, Instrument, and Goal. Ergonomics in Design, July 1995, pp. 1924.

[10]Dinadis, N. and Vicente, K. J. (1997): Designing Functional Visualizations for Aircraft Systems Status Displays. To be published. And: Kim J. Vicente and Nick Dinadis: Status Displays For Engineering Subsystems In Aviation Cockpits: A Literature Review. Cognitive Engineering Laboratory, Department of Mechanical & Industrial Engineering University of Toronto: Gavan Lintern (Ed.): Special Issue on Display Design, Journal of Human Factors in Aviation

for visualization are therefore relevant. In the following paragraphs, visualization at the various levels of abstraction is discussed in more detail with reference to examples of representations within the SEAD/UAV domain, as found in the literature. Based on this collection of examples, a preliminary guide to systematic design of visual, diagrammatic representation is presented.

13.1. The Level of Physical Configuration and Material Form

Represented at this level are the topography of the work system, and the material characteristics of objects, tools and systems elements available to serve processes at the physical process level. The tasks to be supported by visualization are locomotion and navigation in a topography, search for objects and parts, and acts to move, assemble, or connect parts. Conventions for representation of the causal aspects of the work system at this level vary widely with the functions served.

Pictorial representations of a work space include pictures of equipment, blue-prints of machinery, architectural drawings, etc. Pictorial representations supplied by various forms of cameras, video sensors and radar systems are important type of displays for situation assessment in UAV systems.[11] See figure 13.1.

A faithful pictorial representation is necessary for target an threat identification and for image analysis, control of focus, viewing angle (zoom), and other aspects of imaging quality are important to render a good representation. Regarding image presentation, Breda[12] finds from simulator experiments, that target tracking becomes critical for image transmission rates slower than 4/second and concludes:

> "Many attempts are currently made to improve the MUAV downlink transmission bandwidth in order to increase information flow. However, high costs and technological limitations limit progress is this field. Since the decrease in operator performance is caused by lack of anticipation and orientation, it should be investigated whether provisions for enhanced visual information may be a more efficient way to improve operator performance. This should not only concern improvement of the sensor image characteristics, but also improvement of the operator's awareness by depicting additional graphic information onto the sensor image. For example, synthetic perspective graphics, creating a virtual landscape,

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[11] Figure 13.1-3, source: Dennis, R. W. (1995): The Phoenix Target Acquisition and Surveillance System. Paper 19. AGARD Conference Proceedings 591: Subsystem Integration for Tactical Missiles (SITM) and Design and Operation of Unmanned Air Vehicles (DOUAV).

[12] Breda, L. van, (1995): An explanatory Study of the Human-Machine Interface for Controlling Maritime Unmanned Air Vehicles. Paper 21; AGARD Conference Proceedings 591: Subsystem Integration for Tactical Missiles (SITM) and Design and Operation of Unmanned Air Vehicles (DOUAV).

as seen from the actual MUAV position, displayed at a high update rate (i.e., 60Hz). "

This conclusion points to consideration of 'virtual reality' technology for image presentation for the analyst in order to better appreciate the navigation opportunities and constraints of navigation from terrain features and threat envelopes.

Symbolic maps representing the topography of the target area are used for mission planning, see figure 13.2. and 13.3. For UAV launch and recovery planning, topographic displays with overlay of constraints, e. g., as imposed by air traffic controllers are used, see 13.4. & 13.5. This kind of displays includes also the well known 'highway-in-the-sky ' for fighter piloting, see figure 13.6.

Symbolic, topographic maps with symbols indicating locations of interest, cities, airports, traffic routes, etc. are widely used[13] and topographic maps with overlays of symbolic information such as meteorological data, weapons, targets, are relevant for communicating results of primary image analysis and situation assessment upward through an SEAD-UAV organization.

The recoding of topographic maps including symbolic icons representing features of interest such as targets, threats, constraints will change with the decision situation for which the information is intended, both with respect to level of abstraction and span of attention and planning of re-coding to serve the different links among the 'states-of-knowledge' shown in figure 12.1 is a very important display-content and -form issue to be resolved during activity analysis.

The intentional aspects include the selection and configuration of elements intended to serve particular processes, routes and trajectories in the topography to support navigation, etc., together with representation of constraints defining 'safe fields' of travel.[14]

Functional maps and mimic diagrams. Schematic maps of the functional structure of a system without any reference to the location of its elements are widely used in engineering, such as mimic diagrams of electric and hydraulic systems etc., see figure 13.7. This kind of displays are important in support of control and maintenance of technical systems. This kind of displays have been used for traffic control and monitoring for communication satellites and will be relevant for configuration monitoring and de-conflicting of SEAD

[13]Edwin Hutchins: The Integrated Mode Management Interface. Department of Cognitive Science

[14]Gibson, J. J. and Crooks, L. E. (1938): A Theoretical Field-Analysis of Automobile Driving. The American Journal of Psychology, Vol. LI, July, 1938, No. 3. Pp. 453-471

communication networks (e.g., by the Joint Force Director (J6) of Control, Command, Communication, and Computers).

In the present context, such diagrams are important for monitoring and control of on-board UAV systems, as they are being developed also for civil aviation.[15] For examples see figure 13.8. Such functional maps representing the topography of the flow paths followed by information, material, etc. are necessary for trouble shooting and maintenance, and to support an effective topographic strategy for fault finding, overlays showing actual and normal states along the paths are important.

13.2. The Level of Physical Processes.

This level represents the physical processes relevant to the functions of a system as they are constrained by the configuration of the underlying physical components. All purposive acts in a human-machine system serve to shape the material configuration in ways that constrain and guide physical processes so as to serve the intended functional relation between actions and their effects. Visualization should focus on the state of process variables with reference to target states and to the limits of acceptable operation.

At this level also visualization in the form of symbolic diagrams has evolved for particular physical processes within related engineering and natural science disciplines. Well-known engineering examples are phase diagrams for metallic alloys, pressure-volume diagrams for engine cylinders (figure 12.2), phase diagrams for water-steam mixtures, engine-cycle diagrams for different Rankine cycle machines, etc. For an example see figure 13.9 & 10 showing phase diagrams and guide to an effective work process.

At this level we also find symbolic displays for vehicle control, including indication of constraints derived from aero-dynamic analysis of the process as the stall-constraint based WrightCAD display suggested by Flach,[16] see figure 13.11. For UAV and fighter control, a similar 'state-phase' diagram representing the constraint envelope as faced by the operator has been proposed by Flach, see figure 13.12.

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[15] For aviation implies, see Joseph G. Oliver: Improving Situational Awareness Through the Use of Intuitive Pictorial Displays. Aerospace Technology Conference and Exposition Long Beach, California October 1-4, 1990; and
Kim J. Vicente and Nick Dinadis: Status Displays For Engineering Subsystems In Aviation Cockpits: A Literature Review. Cognitive Engineering Laboratory, Department of Mechanical & Industrial Engineering University of Toronto

[16] Flach, J. M. (1997): Ready, Fire, Aim: A 'Meaning Processing' Approach to Display Design. In D. Gopher & A. Koriat (Eds.) Attention & Performance XVII.

13.3. The Level of General Function.

At this level of representation we find functions serving particular purposes and involving various different physical processes. Tasks at this level are the connection, adjustment and coordination of the individual process systems to serve higher level purposes. That is, representation must be independent of the nature of the processes involved. Representation conventions, consequently, have to be based on recurrent, generalizable input-output relationships.

It follows that visualization of functional relationships have to be based on generalized representation of relationships independent of the physical implementation, that is, for technical systems usually in the form of sets of mathematical equations. Several powerful conventions for visualizing systems of mathematical representation have emerged to support causal, event based reasoning of system designers and users, such as root-locus and phase-plane representations of control theory, visualization of the solution of sets of algebraic equations and of statistical data analysis in terms of analytical geometry (e.g., nomograms) or pictorial diagrams of the solution of such equations. This is the field of representation discussed in most texts on data visualization.

Since no reference to a particular physical process and the related laws of nature is required, great freedom is left the display designer to create configural displays representing the operational and intended state and trajectory of a function together with the acceptable limits of performance.

It was mentioned that the diagrams used by professionals for discussing and teaching the deep structure of a domain will be a very relevant source of ideas regarding the *form* of representation. For mission planning for several different UAV systems and SEAD missions, functional diagrams based on constraint representations have been proposed for UAV engagement capability planning.[17] Examples from UAV interception with TBMs are shown in figure 13.14-17. Such diagrammatic representations are well suited for windows to shared knowledge bases during collaborative planning if used with pointing devices and combined with the voice communication channels.

[17] Source: "Chapter 5.3 UAV Engagement Planning" Downloaded from http://208.202.180.2/ UAV-CONSOPDOC/Sec3.htm. (Previous sections and report title not accessible on WWW).

Figures 13.18-19 illustrates the diagrammatic representations used to solve the scheduling problem faced by a multi-UAV system surveying several target areas. [18]

At this level, representation of the intentional context is particularly important. Operations largely serve to make sure that a system function serves the objectives by coordinating the processes serving the function. The primary objectives normally leave several degrees of freedom open within which the operational choice depends on secondary criteria. For instance, the processes involved in the primary objective to transport passengers according to schedule leave options free to a trade-off between safety, cost, and passenger comfort. Since the coordination typically involve decisions taken by the pilot, by flight automation, and by the traffic controller(s) communication of intentions and decision criteria is very important, as demonstrated by the widely discussed 'mode errors' by pilots misunderstanding[19] the behavior of flight automation. Creation of 'direct perception' presenting the intentional control strategy of flight automation, its reason for action, and its actual mode of intervention is an important research issue. The issue is not, as often mentioned, to 'open the black box' of automation (that is, to move to the lower implementation level) to help the pilot to understand its function, but to help him understand the reasons for its actions - which are not found within the box.

Using shared representations is in focus of the CST - Collaborative Systems Technology laboratory of the Armstrong Lab. This program is aimed at the design of information systems for improved collaborative performance during complex missions by effective communication and display of information for transport and battle space management and for intelligence operations. The focus is on support of collaborative adaptation to dynamic and unforeseen situations calling for opportunistic, informal planning and effective coordination among several military services to formulate and achieve shared goals.

The basis of the experimental work is a framework for Adaptive Interfaces for Human-Machine Cooperation.[20] In spite the focus of the title on human-machine interfaces, it presents a cognitive systems engineering approach in terms of a 'work processing framework' aimed at collaborative planning. The

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[18] Source: Siardi, C. (1995): Multiple UMA's In-Flight Management. Paper 22; AGARD Conference on Subsystem Integration for Tactical Missiles (SITM) and Design and Operation of Unmanned Air Vehicles; Ankara, October, 1995.

[19] Sarter, N. B. and Woods, D. D. (1994): Pilot Interaction with Cockpit Automation: An Experimental Study of Pilots' Model and Awareness of the Flight Management System. International Journal of Aviation Psychology, 4, 1-28.

[20] Adaptive Interfaces as an Approach to Human-Machine Cooperation, HCI International Meeting, San Francisco, August '97 By Robert Eggleston.

results of the program will support the discussion of interfaces at the general function level.

13.4. The Level of Abstract Functions and Priority Measures

When several options are open to serve system goals, some priority measures are needed to select the functional structure that serves the system goals best, that is, to close the degrees of freedom left open by the primary system goals, performance measures or optimization criteria, such as cost, efficiency, employee well-being, etc., must be applied.

Priority measures, in general, are related to value carriers that obey the conservation law. Inventories of mass and energy are conserved by laws of nature, while monetary values and numbers of people are conserved by social convention. The invariant concept to be used for visualization thus is the conservation law. Typically, however, conservation laws related to several value measures are relevant, such as flow of energy, mass, monetary values and their separation by analysis of lower level variables will involve complex sets of algebraic equations serving trade-off judgments.

Visualization of the actual state with reference to the intended state within the individual flow systems is often based on analogies to river flow structures, see figure 13.20 for a display representing value flow and accumulation through a commercial company.

This kind of river flow analogy will not reveal the interaction among different flow systems (such as flow of energy and energy carriers (mass)) and the significance of the parameters available for manipulation. Visualization, therefore, may be more effectively based on the conventions for visualizing relationships within algebraic equations by analytical geometry - e.g., in the form of 'trade-off curves.' This approach has been taken by Vicente for displays for controlling nested mass/energy flows, see figure 13.21 & 22.

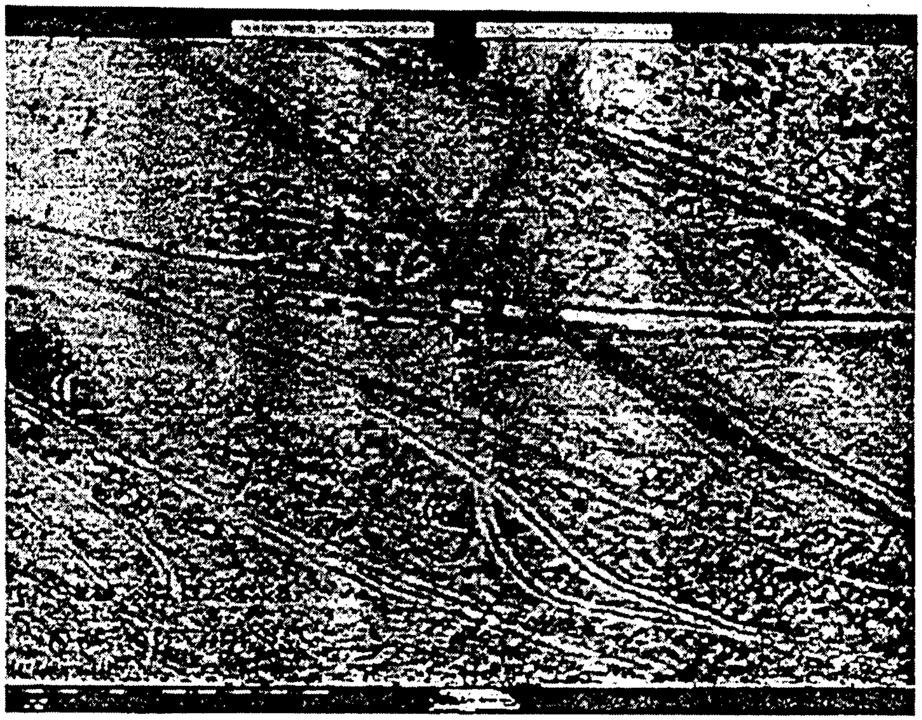

Figure 13.1. A camera image of a target area as it is used for target identification and tracking, situation and battle damage assessment.[21]

[21] Figure 13.1-3, source: Dennis, R. W. (1995): The Phoenix Target Acquisition and Surveillance System. Paper 19. AGARD Conference Proceedings 591: Subsystem Integration for Tactical Missiles (SITM) and Design and Operation of Unmanned Air Vehicles (DOUAV).

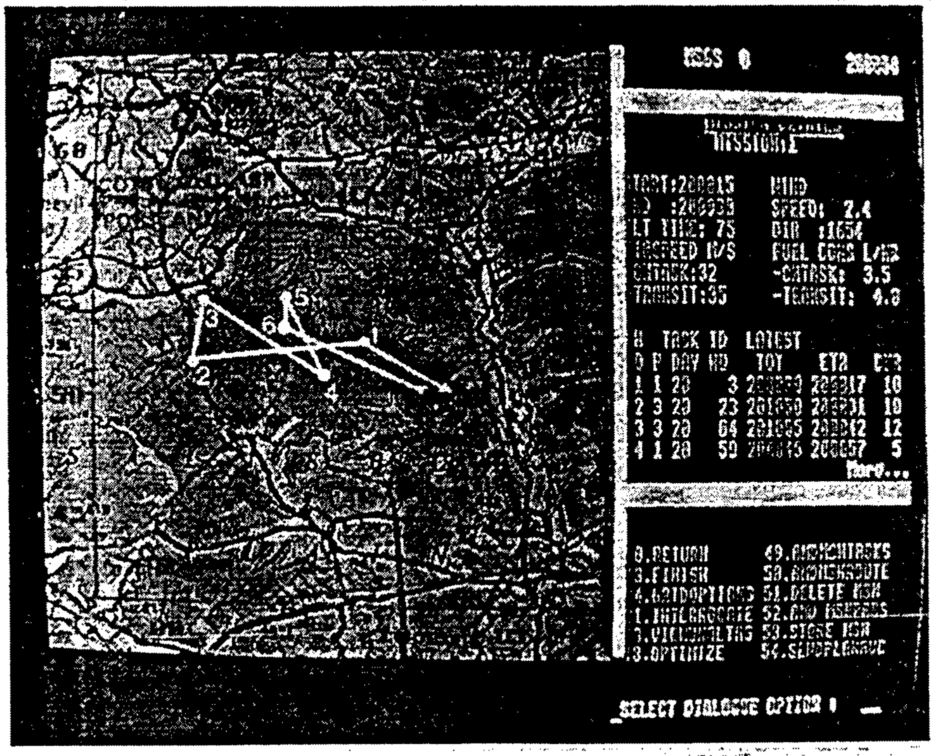

Figure 13.2. A symbolic, schematic topographic map used for mission planning and communication of target identification to higher level planners. For this use, configural overlays are used for communication of results of situation analysis.

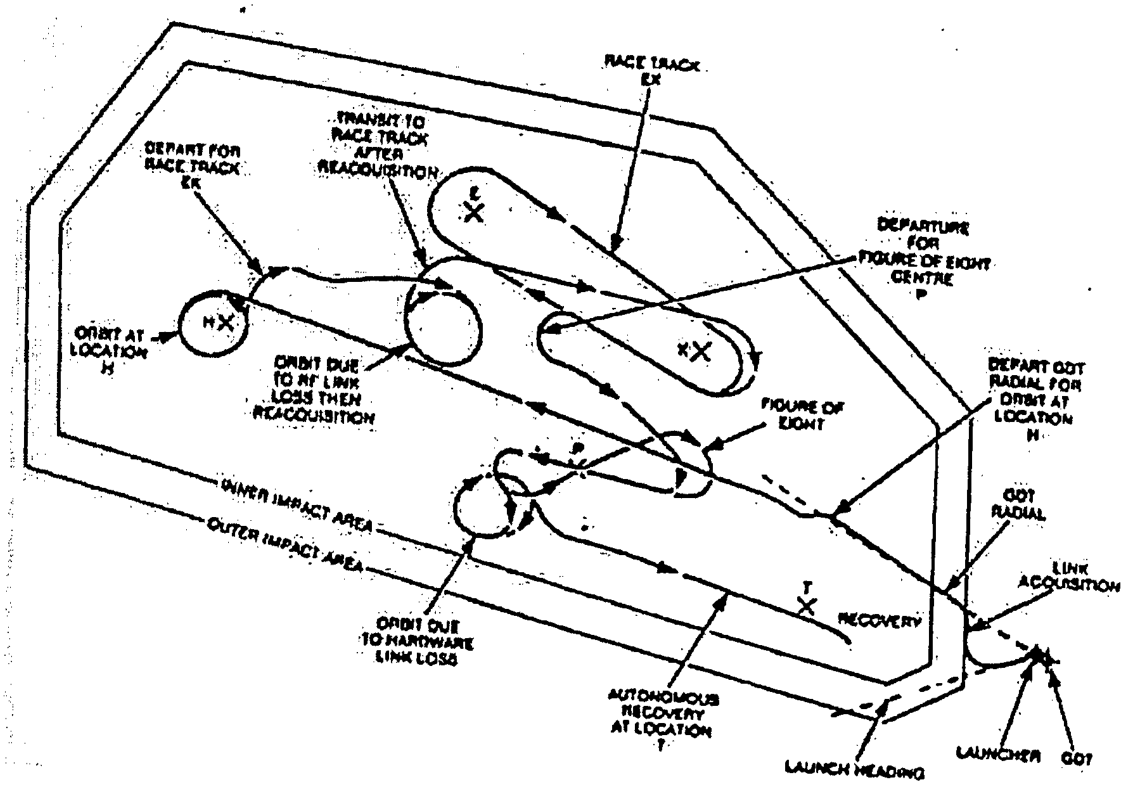

Figure 13.3. Schematic, topographic map used for UAV launch and mission planning.

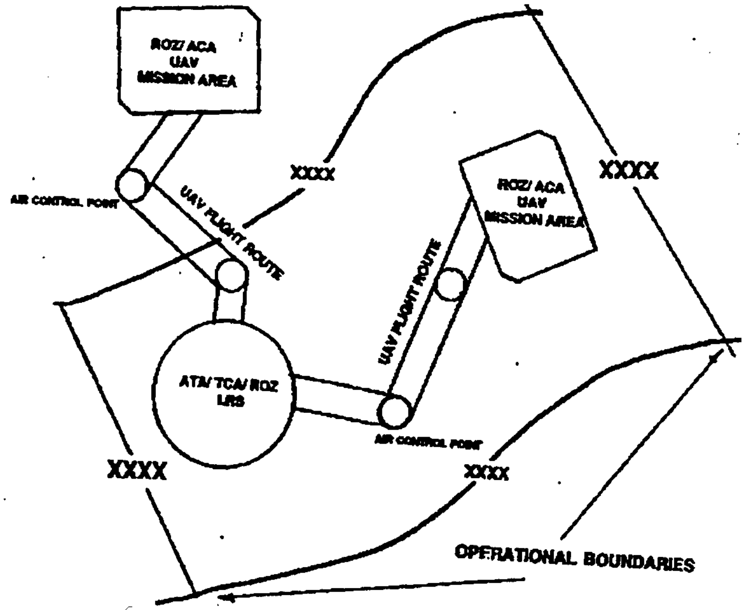

Figure II-3. UAV Airspace Control Measures (Overhead View)

Figure. 13.4. Figure shows overlay for topographic map for coordination of UAV mission with airspace control. 22

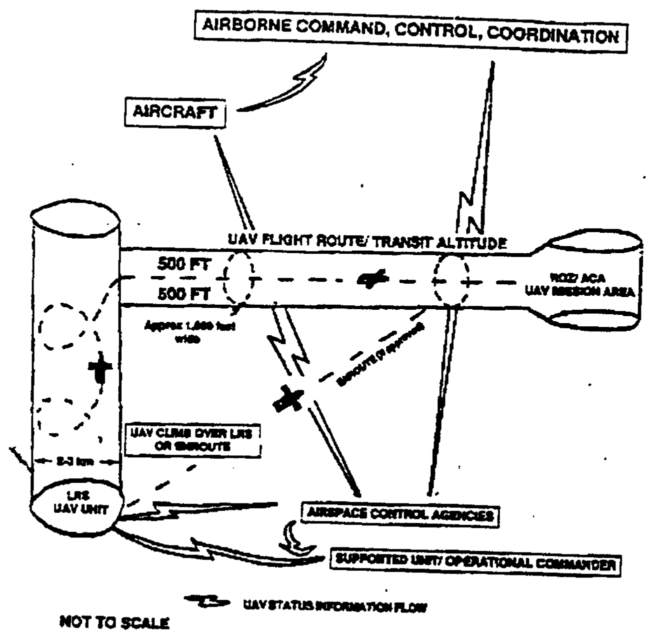

Figure II-4. UAV Airspace Control Measures (Horizontal View)

Figure 13.5. UAV airspace coordination, vertical view.

22 Figure 13.4 & 5 are reproduced from JP 3-55.1; JTTP for Unmanned Aerial Vehicles

Figure 13.6. Pictorial representation with overlay of constraint boundaries: A Highway-in-the-Sky representation of the environment meeting a fighter pilot. It present a dynamically changing representation of the environment as seen from the pilots point of view. Included are representation of the hidden constraints of navigation posed by active (weapons, radar) and passive (tall buildings, towers) as interpreted from knowledge about the dynamic capability of the craft. In this respect, the display includes features of the level of physical configuration for navigation and the level of physical processes for actually flying the craft.

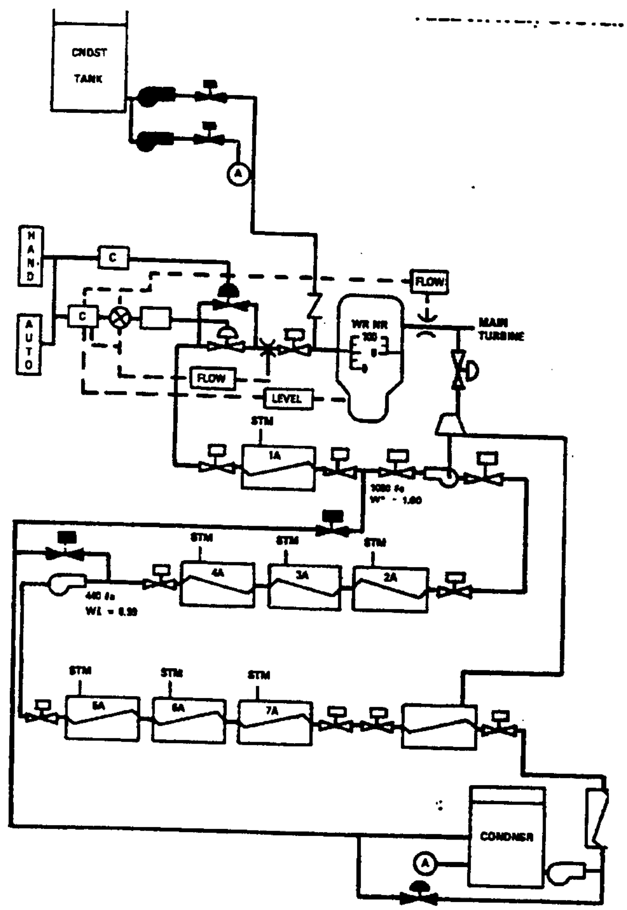

Figure 13.7. A similar schematic, 'mimic' diagram of the feed water system of a power plant. Representation of the physical anatomy of a technical system including objects (means for actions) and their operational availability based on system design, configuration, and running measurements of configuration and availability. The diagram includes a physical analog (mimic) + alphanumeric text) based on professional & other established stereotypical symbols from text books, engineering blueprints, etc.[23]

[23] Display design by Leo Beltracchi, reproduced by permission.

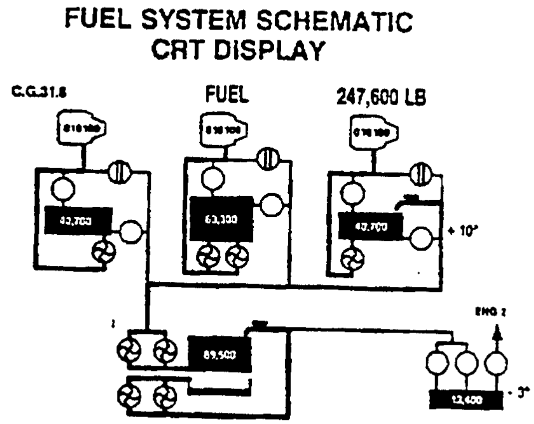

Figure 13.8. A mimic diagram of the engineering subsystem (fuel system) of an aircraft.[24]

[24] Source: Joseph G. Oliver: Improving Situational Awareness Through the Use of Intuitive Pictorial Displays. Aerospace Technology Conference and Exposition Long Beach, California October 1-4, 1990. See also: Kim J. Vicente and Nick Dinadis: Status Displays For Engineering Subsystems In Aviation Cockpits: A Literature Review. Cognitive Engineering Laboratory, Department of Mechanical & Industrial Engineering University of Toronto

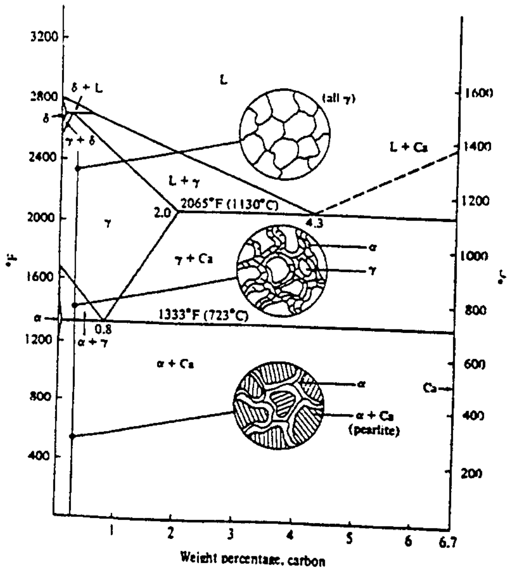

Figure 13.9. Phase diagram of iron-carbon alloy represents the changes in micro-structure dependent on carbon content and temperature.[25]

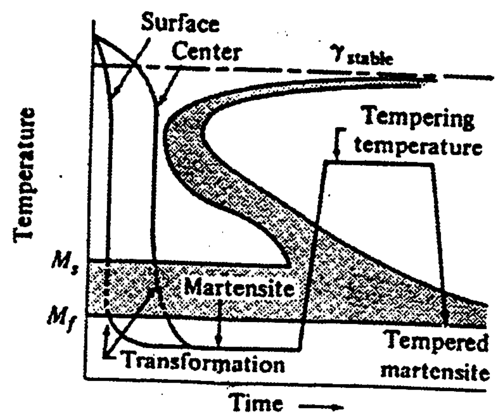

Figure 13.10. Specification of heat treatment of an alloy by the trajectory in a temperature - time map.

[25] Figure 13.9 &10: reproduced from: Flinn, R. A. and Trojan, P. K. (1990): Engineering Material and Their Applications. Boston: Houghton Mifflin.

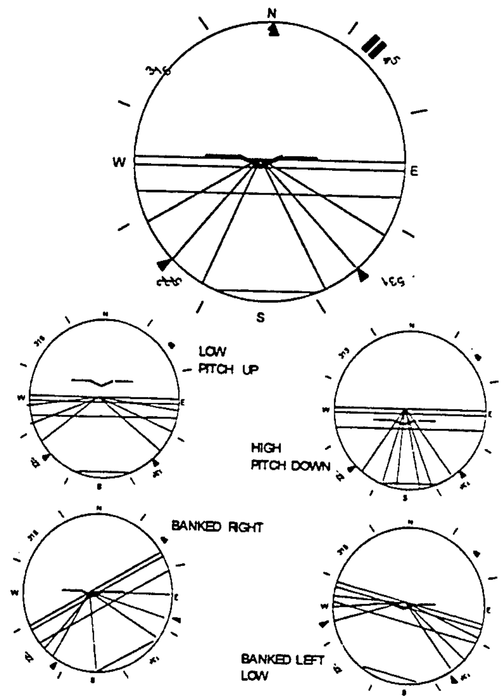

Figure 13.11. The figure shows the WrightCAD display[26] (Flach, 1997) that is aimed at support of locomotion (flight control from the inside). Piloting depends upon a multi-dimensional constraint envelope defined by state variables related to the process of vehicle control, such as altitude, rate of change of altitude, heading, rate of change of heading, pitch, roll, yaw, and their associated rates. These 'hard' data are traditionally shown in separate indicators. Then the 'meanings' such as too low, too high, high enough, too fast, too slow, fast enough, etc.

[26] Source: John M. Flach: Ready, Fire, Aim: A 'Meaning Processing' Approach to Display Design. In: in D. Gopher & A. Koriat (Eds.) Attention & Performance XVII, 1997

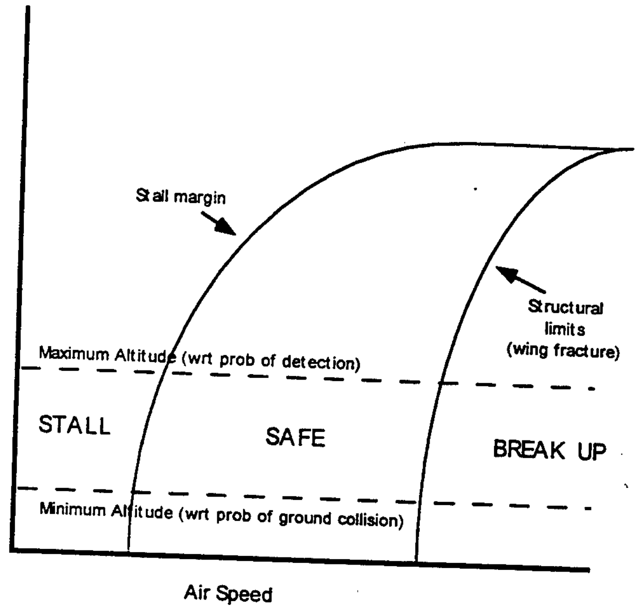

Figure 13.12. A state diagram provides a representation to conceptual bridge between the "physical law based" constraints (e.g., aerodynamic constraints) and "value based" constraints (e.g., the goals of maneuvering mass in a way that will surprise the enemy). The abstract function level of analysis attempts to identify the dimensions of this state space. The boundaries within the space reflect higher order goal (e.g., avoiding detection) and lower lever physical constraints (e.g., stall boundary).[27]

[27] Source: Flach, J.M., Eggleston, R., Kuperman, G. & Dominguez, C. (1998). SEAD and the UCAV: A Preliminary Cognitive Systems Analysis. Final Report. AFRL/HECI: Wright-Patterson AFB, OH..

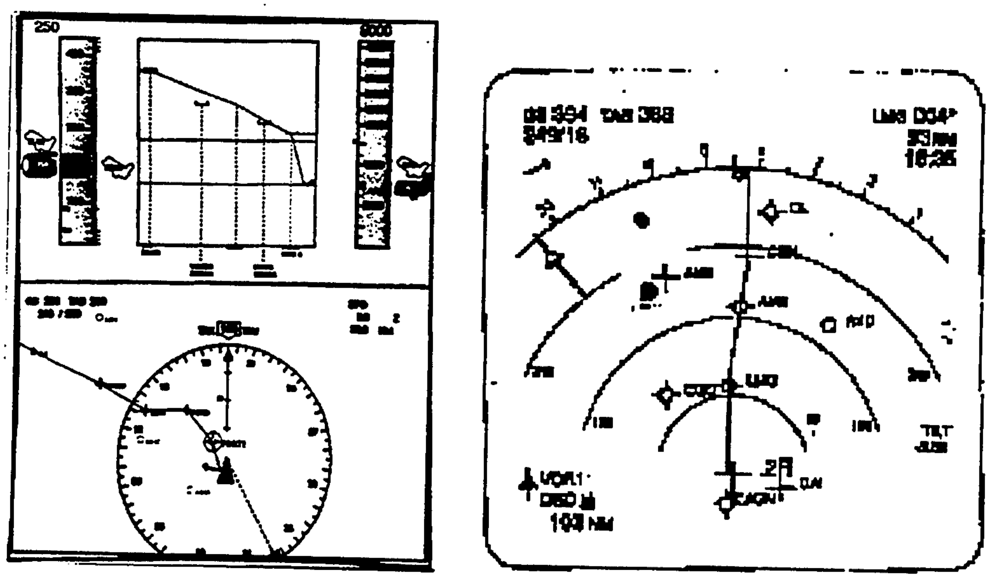

Figure 13.13. The figure shows Hutchins'[28] and Oliver's[29] proposals of a display guiding pilots vertical and horizontal navigation in the three dimensional space of an airport, including the constraints imposed by ATC rules and flight plans. Hutchins' display (left hand side) includes elements of the physical process level, showing the constraints posed by the propulsion system.

[28] Edwin Hutchins: The Integrated Mode Management Interface. Tech. Report. Department of Cognitive Science. University of California, San Diego.

[29] Joseph G. Oliver: Improving Situational Awareness Through the Use of Intuitive Pictorial Displays. Aerospace Technology Conference and Exposition Long Beach, California October 1-4, 1990.

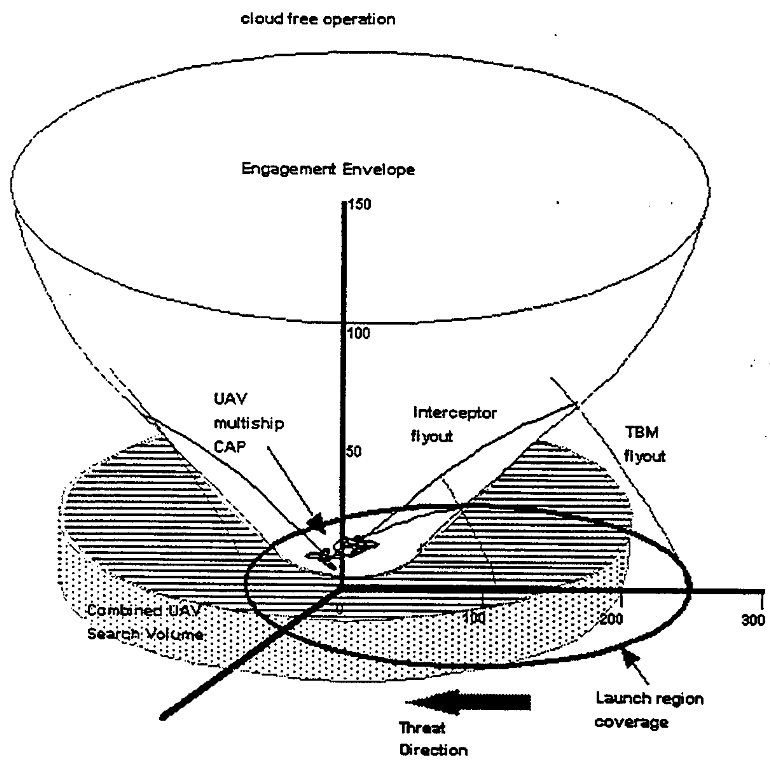

Figure 13.14. Engagement envelope and launch area coverage for TBM interception.[30]

[30] Source of figures 13.14-17: "Chapter 5.3 UAV Engagement Planning" Downloaded from http://208.202.180.2/ UAV-CONSOPDOC/Sec3.htm. (Previous sections and report title not accessible on WWW).

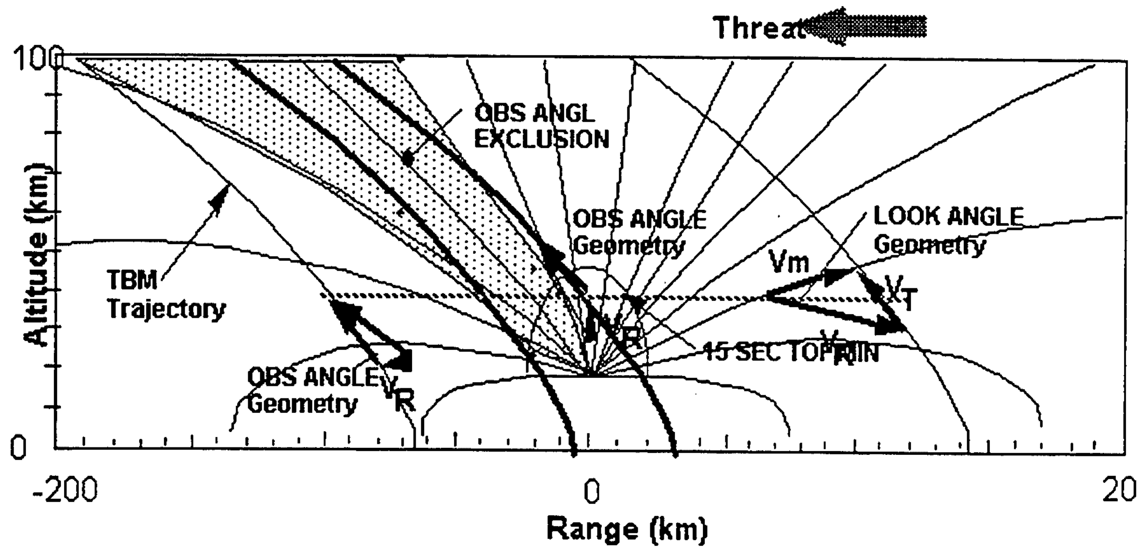

Figure 13.15. UAV-BTM intercept geometry constraints.

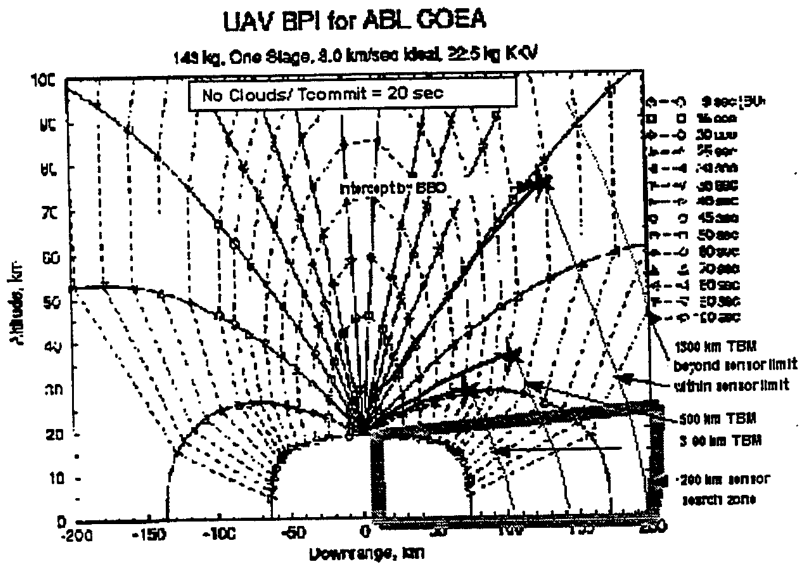

Figure 13.16. UAV intercept limits

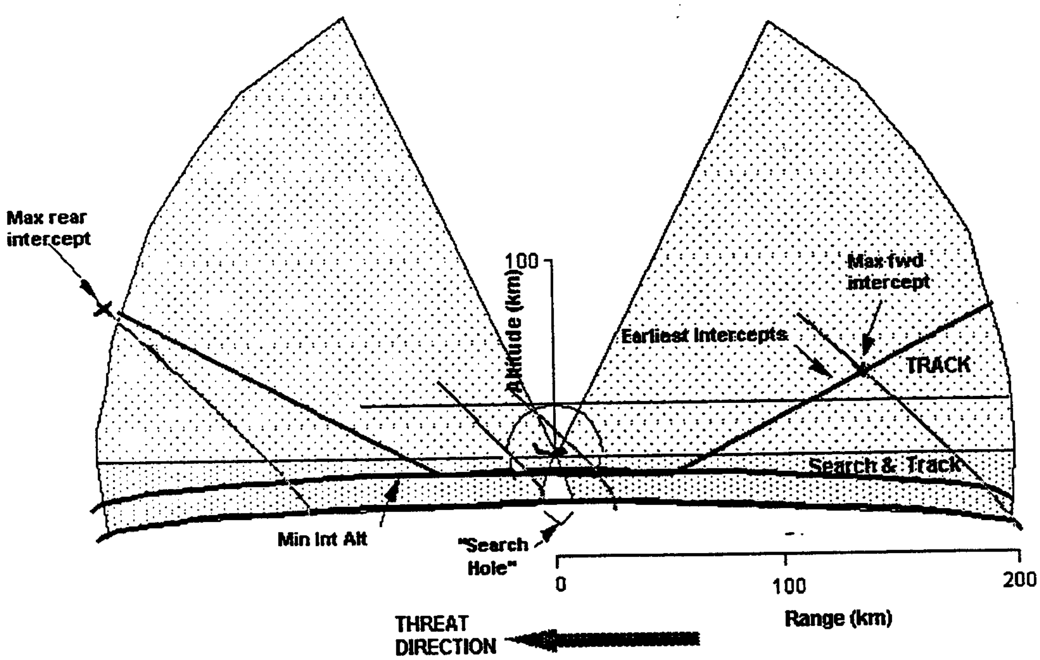

Figure 13.17. Illustration of UAV sensor constraints.

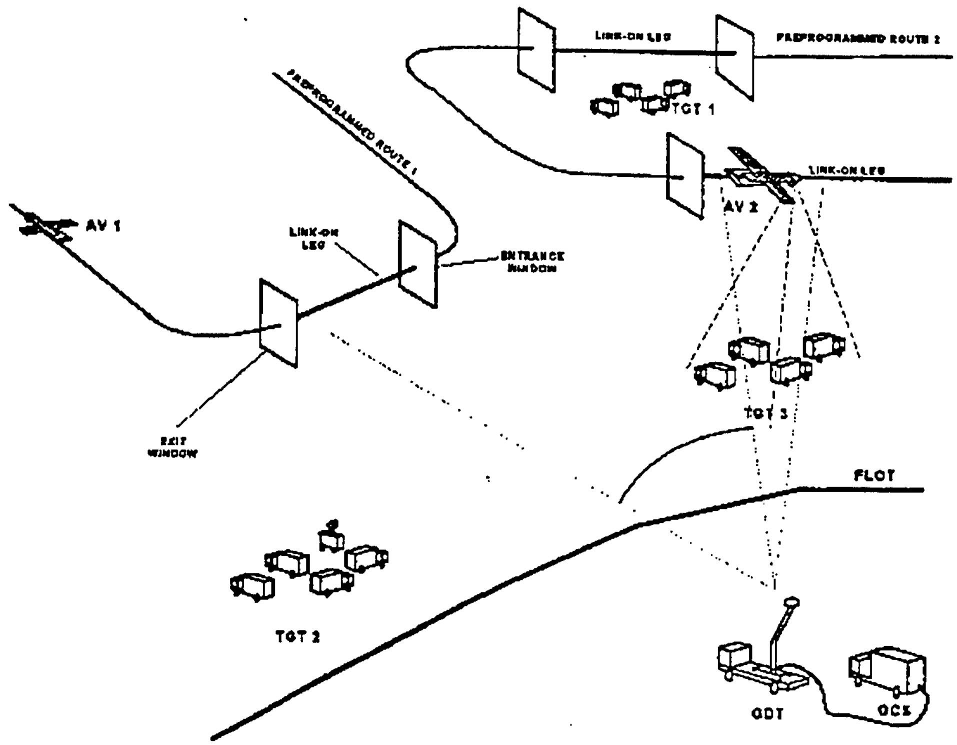

Figure 13.18. The mission planning involving several endurance UAVs monitoring several target areas with only one data link facility involves a very complex scheduling problem.[31]

[31] Source: Siardi, C. (1995): Multiple UMA's In-Flight Management. Paper 22; AGARD Conference on Subsystem Integration for Tactical Missiles (SITM) and Design and Operation of Unmanned Air Vehicles; Ankara, October, 1995.

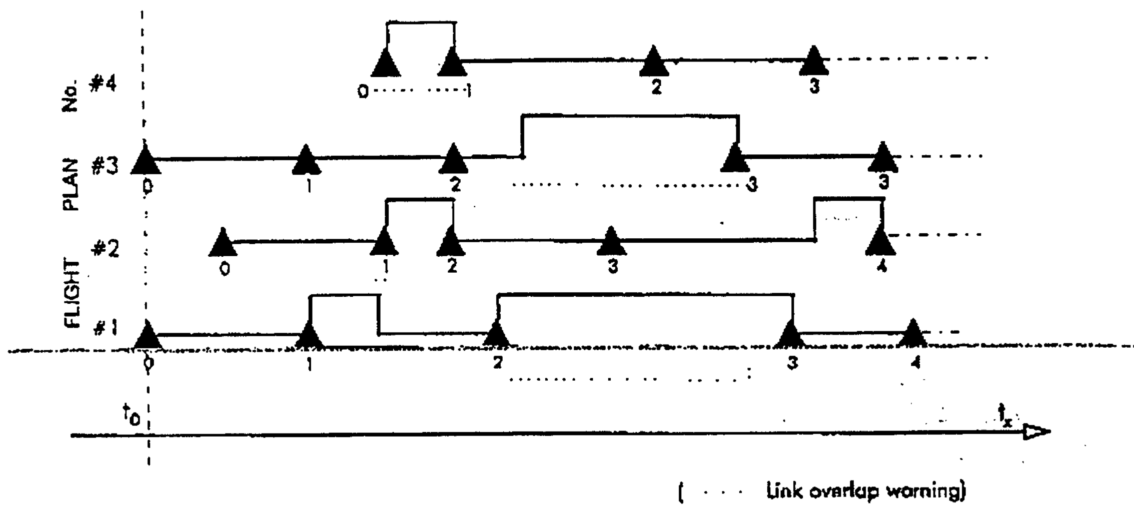

Figure 13.19 illustrates the time-line of the multi UAV scheduling problem of figure 13.18.

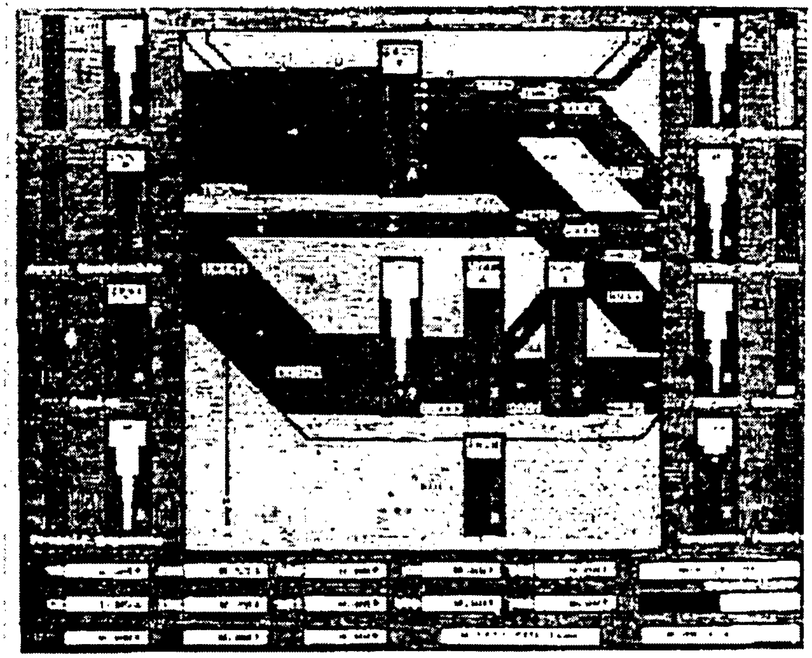

Figure 13.20. A symbolic, metaphorical display using a 'river bed' analogy for representation of the flow of monetary values through a company.[32]

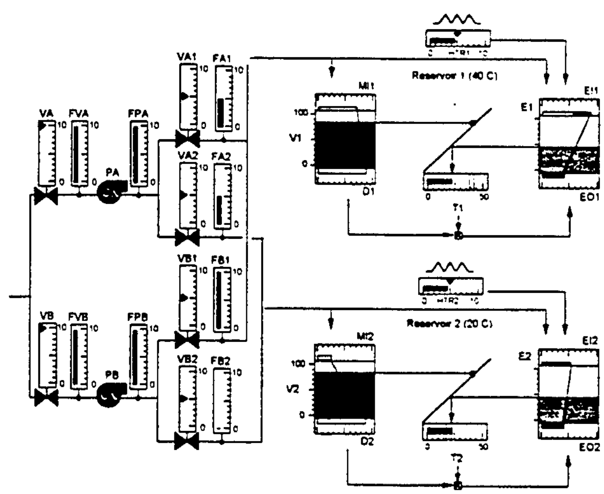

Figure 13.21. Control of a double system of energy/mass flows. It is based on a schematic map of the functional configuration of the system with an overlay of a geometric mapping of the equations representing the mass/energy conservation laws, see figure 13.22.

32 Source: Smith, B., (1992): The Flowsheet: Animation Used to Analyze and Present Information About Complex Systems. Proceedings of the EDPPMA Virtual reality Meeting, Arlington, Virginia, June, 1992. Courtesy B. Smith.

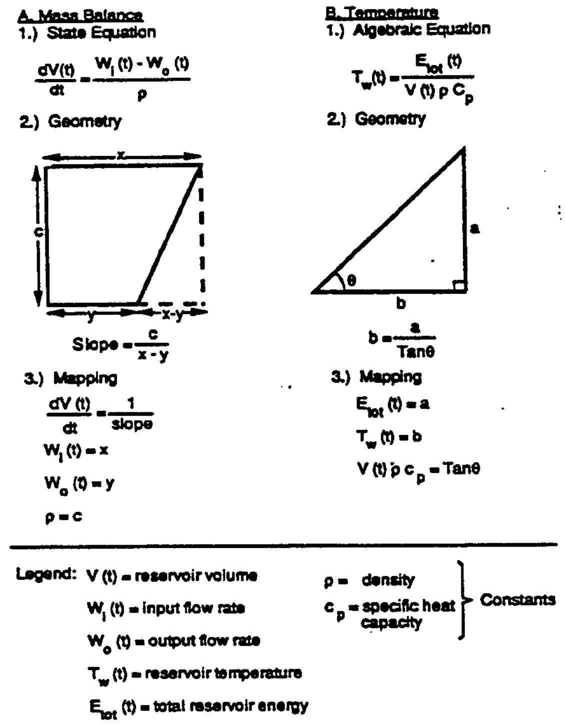

Figure 13.22. Mapping between physical process constraints and geometric constraints in the Duress display shown in figure 13.21.[33]

[33]Reproduced from Vicente, K. J., Christoffersen, K. and Pereklita, A. (1991): Supporting Operator Problem Solving through Ecological Interfaces. IEEE Trans. SMC., 25, 529-545.

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14. An Approach To A Typology Of Graphic Display Formats

The problem to represent the 'deep structure' of phenomena is basically the aim of any science. Therefore, in search of a systematic basis for a typology of visualizations to serve a generalization of the examples in the previous sections, the literature on 'scientific representations' was reviewed. Many approaches has been taken in the various professional domains to support human activities by visualization of data and conceptual relationships.

General studies of scientific representation appear to be mostly found in social science studies of the role of representation in the social interaction in laboratories. An overview[34] shows that the general focus is on various forms of pictorial representation[35] of sets of objects and their spatial relationships (graphic spaces) at various levels of detail (from topographic maps to electron microscopy). Scientific representation is thus generally derived bottom-up from primary data, following the natural science paradigm of objective integration of observed phenomena, except for some engineering representations. This may be the reason, that diagrammatic engineering representations have not been discussed in the literature on scientific representations. Even if 'mathematization' is discussed by Lynch, no discussion of abstract, graphic diagrams is presented. This trend is clear even for recent reviews of representations used in engineering.[36]

This is odd, since diagrammatic representations are widely used in engineering for 'direct manipulation' of conceptual relationships. A systematic comparison of the sources of ideas for visualization of the functional structure of systems appears to be a research need, even if already in 1826 Babbage[37] pointed to this need, and diagrammatic representations offering the potential

[34]Lynch, M. and Woolgar, S. (Eds.), (1990): Representation in Scientific Practice. Cambridge Ma: MIT Press, 1990.

[35]Lynch M. (1990): The externalized retina: Selection And Mathematization in the Visual Documentation of Objects in the Life Sciences. In: Lynch, M. and Woolgar, S. (Eds.), (1990): Representation in Scientific Practice. Cambridge Ma: MIT Press, 1990. pp. 153-186.

[36]Ferguson, E. S. (1977) The Mind's Eye: Nonverbal Thought in Technology, Science, vol. 197, no. 4306, pp. 827-836.
Ferguson, E. S. (1992): Engineering and the Mind's Eye. Cambridge, Ma.: MIT Press.

[37]Babbage, C. (1826): On the Method of Expressing by Signs the Action of Machinery. Philosophical Transactions of the Royal Society, 1826, Part III, pp. 250-265.. London: Royal Society.

for direct manipulation have been systematically developed for engineering use (e. g., for thermodynamics[38] and for control system synthesis[39]).

In other words, little support for generalization covering all the levels of the means-ends representation can be found in the literature. At the present stage, therefore, the path to visualization found in the examples shown above can be summarized as shown in table 14.1. and figure 14.1. The transformation paths related to the various levels are shown in figure 14.2.

Table 1: Map of approaches to visualization
Priority measures:
- Trade-off diagrams representing contribution of alternative functions to priority measure applied,
- Visualization of flow of values, energy, etc.
- Visualization of conservation laws by analytical geometry
General Functions:
- Mathematical diagrams of input-output relations, visualization of algebraic equations, nomograms, root locus diagrams of control theory, analytical geometry
Physical processes:
- Process state diagrams, such as
-P-V diagrams, water-steam phase diagrams, Rankine-cycle diagrams, metallic alloy phase diagrams,
Physical configuration; material form
-Pictures of equipment, blue-prints, circuit diagrams, topographic maps, etc.

Table 14.1. The table illustrates the types of representation applied in typical diagrams within various professions. Figure 14.1 and 14.2. illustrate these levels of visualization and the coding paths taken.

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[38]Gibbs, J. W. (1873): Graphical Methods in the Thermodynamics of Fluids. Transactions of the Connecticut Academy. Pp. 309-342.

[39]Truxal, J. G. (1955). Automatic Feedback Control System Synthesis. New York: McGraw-Hill.

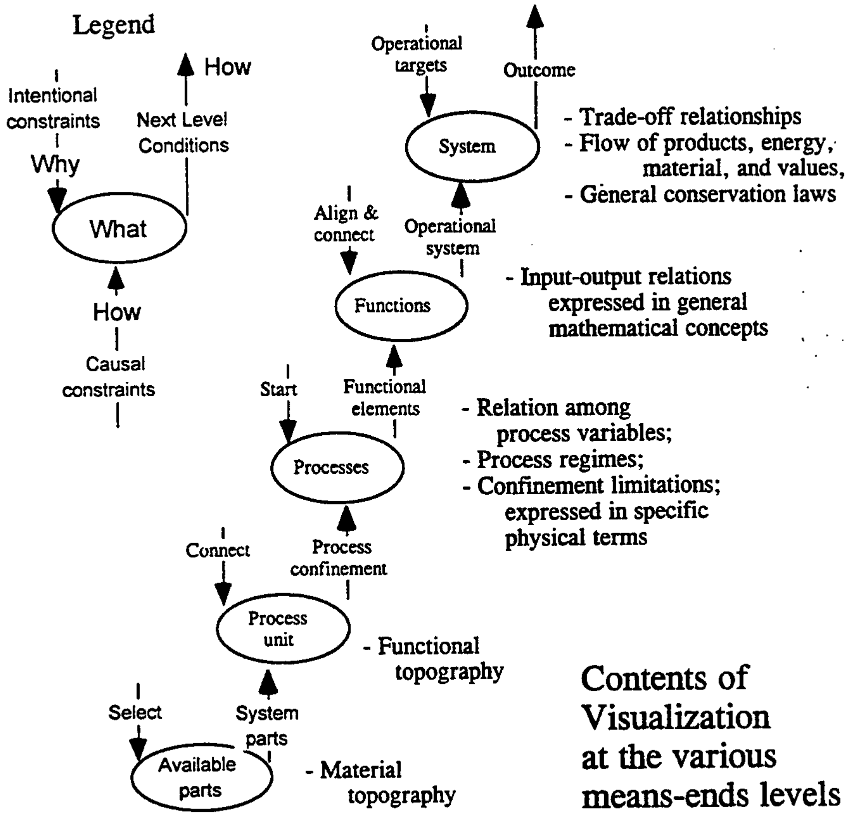

Figure 14.1. An attempt to map the representations relevant for ecological interface design. The figure refers to concepts applied for process control and aircraft onboard technical systems. For piloting and vehicle control, the lower levels must be revised to represent the concepts relevant for locomotion.

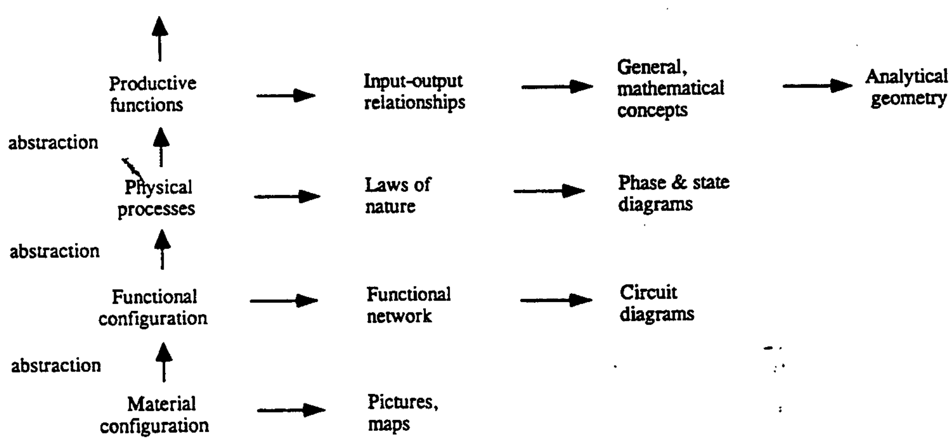

Figure 14.2. Different paths to visualization are relevant at different levels. Therefore, generalization of display concepts relate to different domains.

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15. Guide to Design and Evaluation of Ecological Interfaces

Field studies, interviews of military substance matter experts as well as laboratory studies are required for actual design of an ecological information system to support collaborative decision making during high tempo SEAD operations. Based on the preceding discussion, however, some guides for design and evaluation of interface design can be suggested. In the following sections, the basic phases of design and evaluation analyses are considered.

15.1. Interface Design

The first analysis is focused on creation of the underlying, shared knowledge base.

15.1.1. Knowledge Base

The interface system must be based on a shared knowledge base that represents the requisite variety of functions and resources for all the relevant system mission scenarios. Therefore, the first step of the design process will be to identify the inventory to be included in the knowledge base at all the levels of the means-ends hierarchy, as described in section 7.2. An approach in this direction is evolving in a cooperation[40] between Armstrong Laboratory and Wright State University. This kind of analysis requires cooperation with subject matter experts at all levels of the military mission hierarchy. This cooperation does not only involve interviews and field studies of actual operational behavior during naturalistic military drill sessions, but also involvement of subject matter experts in data analysis. Behavior shaping constraints (causal and, in particular, intentional) are implicit in the practice of expert performers and a kind of reverse engineering[41] of procedures, rules-of-engagement, and observed practice is required to identify the factors and constraints that once in the past shaped behavior.

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40 Flach, J.M., Eggleston, R., Kuperman, G. & Dominguez, C. (1998). SEAD and the UCAV: A preliminary cognitive systems analysis. Final Report. AFRL/HECI: Wright-Patterson AFB, OH..

41 This technique has been used successfully for identification of system constraints from operating procedures for nuclear power plants, see Tanabe, F., and Rasmussen, J. (1997): Simulator experiments with Ecological Interface Systems: A note for Discussion. Work in progress.

15.1.2. Mission Scenario Definition

The next phase will be the selection of a set of prototypical work situations or mission scenarios, to be served by the decision support system and the related interfaces. The set should be chosen to represent a reasonably wide selection of examples with respect to their influence on situational constraints, on role allocation, and on the related cooperative structure. For SEAD missions, a reasonable first approach will be to consider the three mission scenarios that are considered by the doctrines for SEAD (see discussion in section 7.4):

- *AOR/JOA Suppression* (Area-Of-Responsibility/Joint-Operation-Area),
- *Localized Suppression,* and
- *Opportune Suppression*

These three scenarios represent different levels of communication, as illustrated by figure 12.1.

15.1.3. Decision Making Scenarios

For each of these mission scenarios, the structure of the cooperative decision making should be defined, that is, the 'states-of'-knowledge' suitable for communication among members of the mission team. During a SEAD mission planning and execution, information flow upwards from information sources through the military hierarchy of figure 11.1 while data are selected and integrated, see figure 15.1. Then planning-decisions propagate downwards while local details are added for implementation of the plans. In general, communication of details will be necessary between the upward and downward legs, to protect the higher levels from data saturation.

As mentioned in section 7.5, several different functions and processes should be considered for interface design because they relate to different technical system categories, such as:

1. Situation assessment and mission planning related to military strategies and battle control;
2. Control of large, tightly connected information systems supporting intelligence and information dissemination;
3. Operation of work support systems, information retrieval in knowledge bases, operation of mission simulators;
4. Planning 'from the outside' of trajectories to be followed by vehicles in a topographic space (ATC, UAV trajectories in battle space, etc.). Control and monitoring on-board systems;
5. Vehicle piloting 'from the inside' such as remote manual piloting of UAVs.
6. Maintenance of vehicles and technical equipment.

The numbers refer to figure 15.2. Interface design for the work situations numbers 2 to 6 involves rather well defined actors in work situations known from other contexts. Task 2 relates to communication network control in telecommunication and satellite network control; for tasks 4,5 great research efforts are presently made for interface design in aviation in general,[42] while control of on-board systems can draw on research in industrial process control.[43] Maintenance tasks, 6, are also widely studied for process industries and transfer is immediate possible to the present context.

Consequently, in focus of the scenario analysis will be the task number 1: Situation assessment and mission planning related to military strategies and battle control. Not much information is available in the research literature or on the Internet for this analysis, and field studies during realistic maneuvers are badly needed, followed by reverse engineering efforts.

Distinction between three different collaborative decision scenarios appears to be important for interface design:

1) One is the basic ***situation analysis, information dissemination and mission control*** illustrated in figure 15.1. Recent panel discussions[44] on information systems for battle command indicate clearly that such systems are evolving by aggregation of multiple computer based systems developed more or less separately. This leads to severe information display problems and large amounts of equipment not very suited for the turmoil of a battle field. Oddly enough, the discussion often is focused on display equipment, less on the options for an underlying data analysis and integration to match the needs of the individual actor. Apparently the evolution of systems is forced by the latest technology offered by suppliers resulting in a bottom-up aggregation of systems, rather than by a top-down, integrated development based on specifications derived by military analysis of mission needs. This latter approach is actually the aim of a cognitive systems engineering analysis for design of an information system for command and control.

The dissemination of information and plans illustrated in figure 15.1 involves an identification of the 'states-of-knowledge' suited for display of information

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42 A recent review is found in: Rasmussen, J. (1998): Review of the Cognitive Systems Engineering Research at the WPAFB Armstrong Laboratory Human Engineering Division. Dayton Oh.: Logicon Technical Services, WPAFB.

43 This is demonstrated by the recent work of Vicente's group at University of Toronto: Kim J. Vicente and Nick Dinadis: Status Displays For Engineering Subsystems In Aviation Cockpits: A Literature Review. Cognitive Engineering Laboratory, Department of Mechanical & Industrial Engineering University of Toronto

44 Panel on Human-Centered Design of Battle Command Systems. 4th Annual Symposium on Human Interaction with Complex Systems. March 98. Dayton Ohio.

and for communication among decision makers. These decision makers functionally constitute a distributed, hierarchical control system and basically, information going upward should be formatted by selection, removal of local details, and integration into higher levels of the means-ends network of the problem space. Similarly, when decisions are propagated downward, operation will be at levels having increasing degrees of freedom for action. Therefore plans must be reinterpreted and local details added to the information forwarded from above.

The involved decision makers and the criteria dynamically determining an effective division of the shared control function must be identified by a careful analysis of the control requirements of the work space, as described in section 6.4. The implications of the result of this analysis for actual system design should be carefully compared to the command and control organization prescribed by military doctrines and rules of engagement (see figure 11.1). In spite of the obvious need for an adaptive command and control structure and a fast link between viewers and shooters argued also by military theorists (see the quotes in section 2), a change of military doctrines appears to be a long term issue. Consequently, studies of control and command during major maneuvers, design of prototype organizations and information systems, and evaluation by large-scale simulations (for which methodology and equipment is readily available at the Armstrong. Lab., Human Engineering Division) are very much in demand.

2) The next decision scenario to be analyzed is ***selective exploration and verification of information*** see figure 15.3. When information is selected and integrated for dissemination as shown in figure 15.1, the receivers should be able to selectively explore knowledge bases and verify information. This need should be met by a careful information indexing, as discussed in sections 7.3 and 12.4. Research on information retrieval in heterogeneous data bases should be consulted for this design issue.[45]

3) Finally, when command and control are organized as a distributed, adaptive system, support is necessary of ***collaborative planning sessions***, see figure 15.4. Design of such support can draw on the research on 'Computer Supported Cooperative Work' and the studies on collaborative design at

[45] See Pejtersen, A. M. 1986): Design of Intelligent Retrieval Systems for Libraries Based on Models of Users' Search Strategies. In: 1986 IEEE International Conference on Systems, Man and Cybernetics. Washington, 1986. Also the chapters on information retrieval in: Rasmussen, J., Pejtersen, A. M. and Goodstein, L. P. (1994): Cognitive Systems Engineering. New York: Wiley

Armstrong Lab.[46] that also has the resources necessary for experimental evaluation of support tools (the CDT lab.). For this function, active 'white boards' have been suggested[47] for sharing sketches and notes and offering externalized shared mental models for pointing and discussion.

15.1.4. Display Design

The design of interface displays is discussed in detail in section 13 and examples of configural displays for task situations 2-6 in figure 15.2, matching the ecological design requirements are, as shown, presently emerging from several sources. Development of ecological displays for task situation 1 of figure 15.2, situation analysis, information dissemination and mission control is still a research topic, and field studies involving military subject matter expert will be required as a basis for the 'reverse engineering' efforts mentioned above.

15.2. Interface Evaluation

A general approach to information system evaluation as an integrated part of system design is described elsewhere.[48] Further development of full-scale simulator evaluation of ecological interfaces for control of technical systems has been made for displays for nuclear power plants based on reverse engineering of operating procedures.[49,50] This work has been focused on evaluation of ecological interfaces designed to induce in operators a faithful mental model of the internal constraints of the work system. Therefore, evaluation is aimed at an analysis of the operators adaptation to the new interfaces during the experimental sessions. The evaluation program therefore has several different phases:

1) First phase is aimed at a verification of the match between the design hypothesis and the resulting system, see figure 15.5, that is, the question is: Is the design right? –Does it work the way intended? The experimental

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46 See a review in: Whitaker, R. D., Selvaraj J. A., Brown, C. E., and McNeese, M. D. (1995): Collaborative Design Technology: Tools and Techniques for Improving Collaborative Design. Wright-Patterson AFB: AUCF-TR-1 995-008 6.

47 Panel on Human-Centered Design of Battle Command Systems. 4th Annual Symposium on Human Interaction with Complex Systems. March 98. Dayton Ohio.

48 Rasmussen, J., Pejtersen, A. M. and Goodstein, L. P. (1994): Cognitive Systems Engineering. New York: Wiley

49 Tanabe,F., Yamaguchi,Y. and Rasmussen, J.(1998): Simulator Experiments with Ecological Interface System. JAERI-Research Report, June, 1998, To be published.

50 Yamaguchi, Y., Furukawa, H., and Tanabe, F. (1998): Design of Subject Training on Reactor Simulator and Feasibility Study – Toward the Empirical Evaluation of Interface Design Concept. Enlarged Halden Programme Group Meeting. March 98. Lillehammer, Norway.

subjects during this phase therefore are the interface designers themselves. Only they can judge whether the resulting system works as intended.

2) Next, subject matter experts understanding the basic functionality of the technical system are subjects for experiments. In this way, the operational biases and heuristics of operators of the previous systems are avoided. Data collection is established from the very start, because the ease of adaptation to the new interfaces is a measure of its usability.
3) The third phase of experiments involve professional system operators and again, data collection covers all sessions from the start to follow the adaptation and the ability of the new interfaces to create the proper operators' mental models
4) Finally, complete novices, e.g., university students, are used as subjects to judge how transparent the interfaces are to complete novices. In this case, pre-experimental training in the basics of system functions and representations clearly will be necessary and the sessions serve to determine the initial competence that should be given to novice operators to 'synchronize' them to the interface design and make adaptation effective.

For the latter three phases, a basic question is the initial competence that should be given to subject to 'synchronize' them to the interface design and make adaptation effective.

Preliminary results from the Japanese program seem to indicate that this approach to display evaluation is very effective. Please note, that the sequence of experimental phases is opposite of the normal academic practice, which also normally do not involve phase 1 and 2.

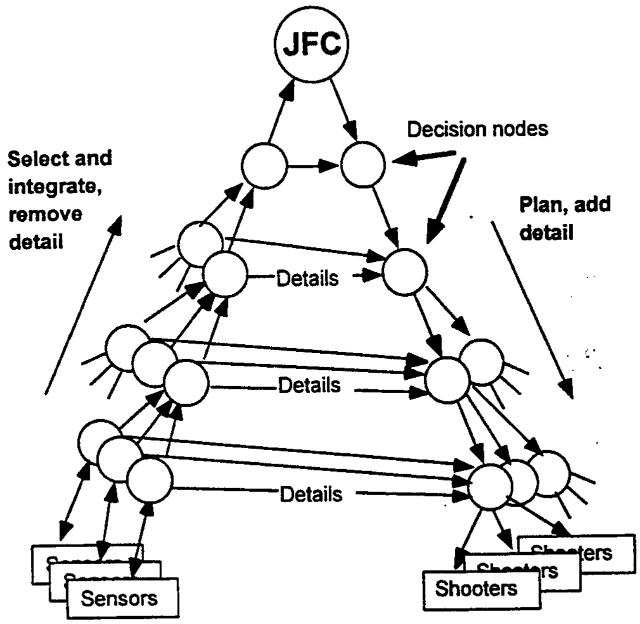

Figure 15.1. During a SEAD mission planning and execution, information will flow upwards from information sources through the military hierarchy of figure 11.1 while data are selected and integrated. Following planning, orders will propagate downward, needing local details for implementation.

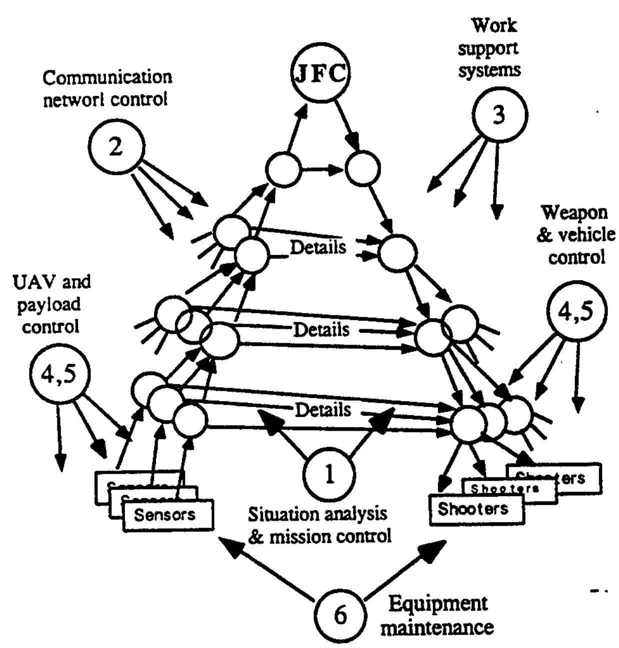

Figure 15.2. Different mission functions are relevant for separate consideration during interface design.

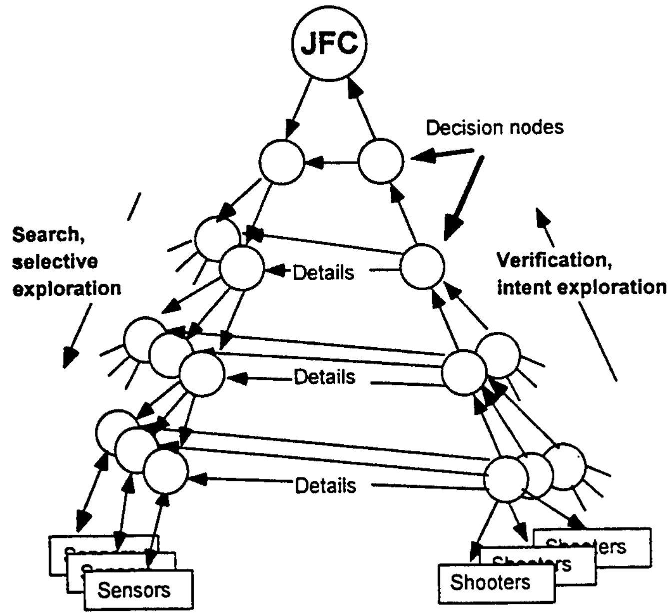

Figure 15.3. When information disseminated routinely has been selected and integrated, a need exists to be able to selectively explore knowledge bases and verify information.

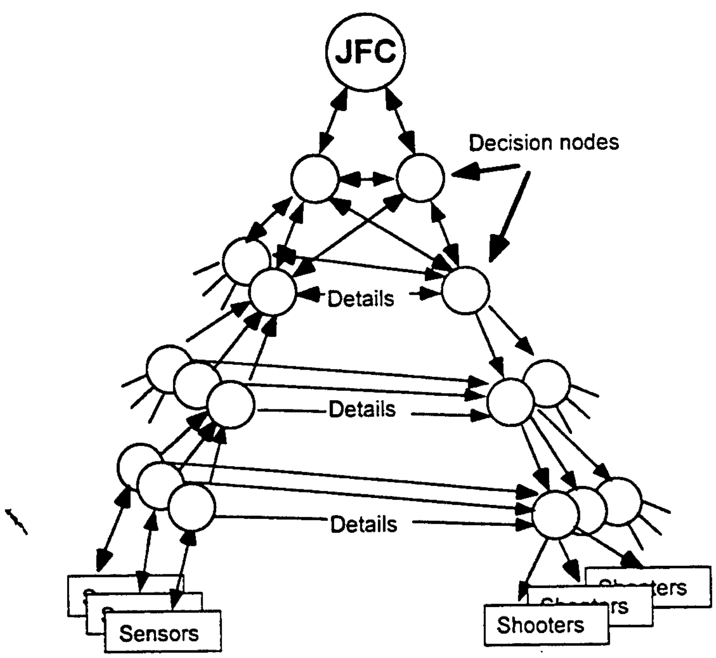

Figure 15.4. For collaborative planning during high tempo situations, the command and control system must include facilities for 'Computer Supported Cooperative Work.' For this function, active 'white boards' have been suggested for sharing sketches and notes and offering external shared mental models for pointing and discussion.

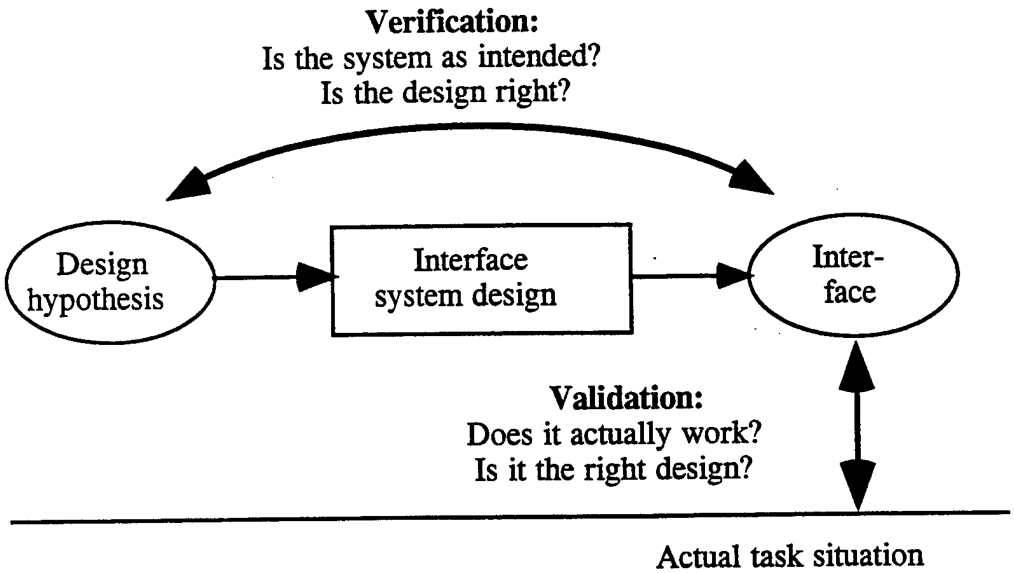

Figure 15.5. Evaluation of an interface design by full-scale simulator experiments involves two consecutive phases. First, *verification* serves to judge the match of the functionality of the interface to the design intentions. Next, *validation* serves to judge whether the design actually works.

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16. Conclusion

It appears from this review that the cognitive systems engineering framework serves well to capture the complexity of the context within which the UAVs will be introduced. It also is well suited to plan an integrated command-and-control structure for complex SEAD missions, a need advocated by several military theorists (see the quotes in section 2) and mentioned explicitly by the recommendations of the Air Force Scientific Advisory Board:

> "The ability to understand what is occurring in the battle space has made the Air Force aware of C2-imposed limitations on combat effectiveness. As a consequence, the true potential of aerospace power has not been completely realized."

In addition, several present trends in the research aviation and process control interfaces also points in the direction of an explicit representation of the deep structure of the work space.[51] This seems to indicate that the timing is right now for efforts to apply Cognitive Systems Engineering to design of UAV interface systems.

There are, however, other dimensions of the design problem to consider carefully, related to the question whether cognitive engineering research on command-and-control systems can influence military practice.

One question is the contrast between the formal military rank system and the adaptive, distributed, and collaborative decision making that will be essential during a high tempo SEAD. Analyses of the collaborative structure onboard an aircraft carrier demonstrate (see section 11.1, p. 81) a pronounced ability of the organization to shift between a formal rank organization and a self-organizing 'high-tempo' work coordination in response to the immediate requirements. Will the same feature be realistic during a SEAD mission, considering the present military doctrines and 'rules-of-engagement? In contrast to a battle theater and the active management of weapons during a SEAD mission, an aircraft carrier is a rather stable and well defined domain, and taking down fighters does not involve active use of weapons. For the SEAD information system, the conflict between the formal ROE doctrine and the need for high tempo adaptation should be studied separately in cooperation with military subject matter experts.

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51 For a review of related cognitive systems research and the WPAFB Armstrong Lab. program, see: Rasmussen, J. (1998): Review of the Cognitive Systems Engineering Research at the WPAFB Armstrong Laboratory Human Engineering Division. Dayton Oh.: WPAFB Logicon Technical Services.

Another question is the present military practice to let complex systems evolve bottom-up by aggregation of the latest technology offered by suppliers.[52] In order to influence this practice toward a top-down specification of new systems based on a cognitive systems engineering approach, it will be necessary to demonstrate the potential benefit to military and industrial stakeholders by a well organized presentation of prototype systems evaluated by use of full-scale system simulation.

As argued elsewhere,[53] the Armstrong Lab. Human Engineering Division in cooperation with the Wright State and Ohio State universities present an extraordinary potential with respect to experimental facilities and cognitive systems engineering methodology. A joint effort focused on top-down design of a prototype SEAD system could very quickly make a visible impact on the discussion of the two problems mentioned above.

Actually, initiatives such as the ACTD concept, that is, the Advanced Concept Technology Demonstration, applied for the endurance UAV systems[54] appears to invite the participation of the AL Human Engineering Division in system specification and design of a SEAD command-and-control system:

> "The ACTD strategy for development and acquisition provides a streamlined method for working closely with the user to rapidly demonstrate and field a new capability in limited quantity. ACTDs provide a critical step in evaluating the military utility of new technologies before commitment to acquisition. ACTDs are intended to reduce acquisition risks and uncertainties at relatively low costs. Major investment is delayed until demonstration of the value and maturity of the technology is proven. The ACTD process will continue to be an integral part of the evolution of the endurance UAV concept. For the Predator UAV system, which is the first to graduate from ACTD status, it is important to understand that the only stated requirement for the conclusion and declaration of a successful ACTD is to field a system that has some measure of military utility. The only endurance UAV ACTD requirement is to conclude this process within a budgetary constraint."

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52 See the discussion in: Whitaker. R. D. and Kuperman, G. G. (1996): Cognitive Engineering for Information Dominance: A Human Factors Perspective; Tech. Report AL/CF-TR-I 996-01 59.

53 Rasmussen, J. (1998): Review of the Cognitive Systems Engineering Research at the WPAFB Armstrong Laboratory Human Engineering Division. Dayton Oh.: Logicon Technical Services, WPAFB.

54 Steele, R. D.: Intelligence and Counterintelligence: Proposed Program for the 21st Century; Section 1.1.4. Found at: WWW.oss.net/OSS21